INVESTIGATION OF HEATLESS DESORPTION TECHNOLOGY FOR CARBON DIOXIDE CONTROL IN MANNED SPACECRAFT

By Martin Lieberman and Alvin Skopp

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LANGLEY RESEARCH CENTER

HAMPTON, VA.

Esso Research and Engineering Company

Government Research

Linden, New Jersey

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        This report describes the studies carried out by the Esso
Research and Engineering Company for NASA under Contract NAS 1-9356.
The work was conducted during the period August 1969 to November 1970.

        The authors wish to express their appreciation to Mr. Rex Martin
of the NASA Langley Research Center who acted as contract monitor for
this program.

ABSTRACT

This report describes the results of an investigation to improve the cyclic process of physical adsorption for removing carbon dioxide and water vapor from air using molecular sieve and silica gel sorbents. "Heatless Desorption", a fractionation process not requiring the addition of heat energy, was investigated to develop system design criteria appropriate for manned spacecraft application.

Primary emphasis was given to evaluating: (1) Low purge-to-feed ratios, low space velocity, and a composite bed of two sorbers for water vapor removal, and (2) the use of purge gas which would otherwise be vented to vacuum to increase the rate of vacuum desorption of CO_2. The use of "Heatless Desorption" for air conditioning in space without a radiator or refrigerant was examined. Potential applications of "Heatless Desorption" were studied including an add-on water save system for the primary Skylab vacuum desorbed system.

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SUMMARY

This report describes the work conducted by the Esso Research and Engineering Company for NASA under Contract NAS 1-9356. The purpose of this work was to continue studies started under an earlier contract, NAS 1-6918, to evaluate the application of Esso's proprietary Heatless Desorption process (also referred to as Heatless Adsorption) (CR-66582) to carbon dioxide control in manned spacecraft.

To date, most investigations of molecular sieve regeneration have centered on the use of vacuum and/or heat desorption.

Heatless Desorption is a low power, rapid cycling, two-bed process that can remove selected components from gaseous streams. The process uses a gas at reduced pressure as a purge for reactivating the adsorbent. The purge can be either a portion of the product from the adsorbing bed, or alternately, a portion of the depressure gas. The Heatless Desorption method of sorbent regeneration is effective for many applications and it usually results in savings in adsorbent weight and power requirements.

The study reviewed in this report was primarily aimed at (1) defining the Heatless Desorption process performance for more specific spacecraft applications than was feasible previously, and (2) examining modifications of the basic system mode of operation.

The first phase of this study involved the use of the Heatless Desorption process for drying the carbon dioxide contaminated air. Major emphasis in this part of the study was given to evaluating the effect of lower purge to feed ratios and space velocities than in the first program. The use of a two zone, silica gel-molecular sieve desiccant bed was also investigated.

For the drying studies, purge to feed ratios of 1.03 to 1.10 and space velocities in the range of 28 to 48 ft.^{3}/hr.-lb. of bed were used compared to purge to feed ratios of 1.1 to 1.2 and space velocities of 93 and 156 CFH/lb. bed used in our earlier NASA work. It was found that a favorable operating process variable trade-off could be made between space velocity and purge to feed ratios to yield acceptable product water concentrations. Typically, a space velocity of only 28 ft.^{3}/lb. of bed and a purge-to-feed ratio of 1.05 gave equivalent drying capacity to a space velocity of 156 ft.^{3}/hr.-lb. of bed and a purge-to-feed ratio of 1.21. A parametric drying equation, developed during the 1966 program, was found to accurately predict the performance of the Heatless Desorption drying unit down to a purge-to-feed ratio of 1.05 and a space velocity of 28 ft.^{3}/hr.-lb. of bed.

The use of a two zone silica gel, molecular sieve bed was found to reduce the steady state effluent water concentration below that produced by silica gel alone for comparable levels of space velocity and purge to feed ratios. Performance was found to be dependent on the relative amounts of molecular sieve and silica gel used with a critical sieve to silica gel ratio required to obtain very dry air (<50 ppm H_2O at low space velocities 28-48 ft.^{3}/lb. of bed and low purge to feed ratios. The performance of the 13X molecular sieve-silica gel two zone system appeared to be slightly better than the 5A molecular sieve silica gel system.

The second phase of this program involved a study of the Pressure Equalization Depressuring (PED) purge technique, found to be the preferred purge technique in the first study, for improving the CO_2 capacity and air loss characteristics on the molecular sieve beds.

In this study, an increase in PED cylinder volume, and the addition of sieve to the PED cylinder to increase its storage capacity, were examined as ways of improving system performance. Heating the purge and delaying its use were also investigated as ways of increasing system performance.

The use of larger PED cylinders was found to effect a modest increase in system CO_2 removal capacity without incurring any appreciable air loss. Increasing the PED cylinder volume by a factor of 3 results in a 15 to 25% increase in system capacity.

No improvement in Heatless Desorption CO_2 system capacity was observed through the use of a sorbent filled PED cylinder; air loss rates appear to be slightly higher using this PED mode configuration. The most probable explanation for the failure of this concept to improve CO_2 capacity is an insufficient PED desorption vacuum pressure resulting from the combined effects of PED sorbent outgassing and pressure drop through the desorption bed.

The use of a PED heated purge did not improve CO_2 system performance. This was primarily a result of the fact that very little elevation in bed temperature took place during PED desorption; i.e. the mass of the beds were much greater than the mass of the gas used during the cycles.

Delaying the discharge of the PED purge improved system performance. Delaying the purge for 25% of the 1/2 cycle time can result in as much as a 35% reduction in air loss rate for comparable system capacities.

Heatless Desorption CO_2 system performance using 13X Molecular Sieve is slightly poorer than with the 5A Sieve.

Heatless Desorption CO_2 removal capacity increases in a near linear manner with an increase in CO_2 feed partial pressure. Increasing the partial pressure from 4.0 to 6.8 mm Hg resulted in about a 3 fold increase in system capacity and about a 4 fold decrease in system air loss rate.

The use of a Heatless Desorption drying system for air conditioning, as well as CO_2 control, was reviewed for a space shuttle mission. In addition, the use of Heatless Desorption for providing supplemental drying for Skylab was found to be an attractive application.

1. INTRODUCTION

In order for a crew to survive and function in space, they must be provided with a suitable gaseous environment, controlled with respect to composition, temperature, and pressure.

Systems for carbon dioxide control in spacecraft have been proposed based on the use of both regenerative and non-regenerative carbon dioxide adsorbents. As missions increase in length, regenerative carbon dioxide systems will be needed to minimize total system weight.

Currently synthetic Molecular Sieves are the preferred adsorbents for use in such systems. These highly porous, crystalline, alumino-silicate compounds have a relatively high capacity for carbon dioxide, even at low partial pressures (1-10 mm Hg absolute). Molecular Sieves, however, have a greater affinity for highly polar compounds such as water than that for carbon dioxide. Consequently, a Molecular Sieve system must include provision for pre-drying the gas before carbon dioxide can be removed. This complicates the system somewhat, but on the other hand, provides flexibility in adapting the process to different requirements of material conservation.

A carbon dioxide control system could be designed for three different modes of operation as shown in Table 1. Laboratory demonstration systems have been designed and fabricated and evaluated for these operations. In general, these systems have used thermally regenerated silica gel desiccant and vacuum or thermally regenerated molecular sieves. Silica gel has generally been the preferred desiccant material since it posseses a relatively high capacity for water and yet is quite selective, having almost no affinity for carbon dioxide, oxygen and nitrogen.

Table 1

Conservation Options in CO_2 Control Systems

H_2O	CO_2	Typical Mission
Reject to space	Reject to space	Skylab A
Recover	Reject to space	Desirable for later Skylab missions
Recover	Recover	Necessary for a large space station

In any regenerative adsorption process, the technique used for regeneration of the adsorbent material is a key factor in establishing the overall effectiveness of the operation. Reactivation can be accomplished in several different ways. A few techniques are: heating the sorbent to temperatures at which its equilibrium capacity for the adsorbate is very low; reducing system pressure, thus disturbing the solid-gas phase equilibrium of the adsorbed component; and using a displacing agent, a compound more strongly adsorbed than the component to be removed which replaces it on the adsorptive sites.

Each of these methods has shortcomings. If waste heat is not available, thermal cycles may require a prohibitive amount of electric power for heating. This heat is then lost or requires elaborate heat exchange equipment for partial recovery. Vacuum desorption cycles are usually diffusion rate limited and so may require larger beds of adsorbent than are desirable. Regeneration employing a purge stream results in a rapid desorption of the contaminant gas. The heatless Desorption Process utilizes such a regeneration method.

Heatless Desorption is a low power, rapid cycling, two bed process that can remove selected components from gaseous streams*. The process uses a purge gas at reduced pressure to reactivate the adsorbent in one bed, while a second bed is adsorbing the contaminant at higher pressure. The purge can be either a portion of the product from the adsorbing bed or a portion of the depressurization gas.

In research completed for NASA in 1966 (Contract NAS 1-6918), the Esso Research and Engineering Company evaluated the use of the Heatless Desorption process for the removal of H_2O and CO_2 from spacecraft air.

The research (NAS 1-9356) reported herein represents a continuation of the 1966 program; it has been primarily aimed at further defining the Heatless Desorption process performance for spacecraft application and to improve this performance through modification of the system basic mode of operation.

The report first discusses the fundamentals of the basic Heatless Desorption process in section 2, including a description of the modifications in the system that reduce air loss. In section 3, the drying sub-system development studies are discussed. The process parameters that affect drying performance and the experimental equipment for the drying sub-system studies are described; also, the performance of the system using low purge to feed ratios and low space velocity process conditions are presented. Heatless Desorption drying performance using two zone, silica gel molecular sieve desiccant beds is also described.

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* The Terms Heatless Adsorption and Heatless Desorption are synonomous. However, the latter more aptly describes the process.

In section 4, the results of the CO_2 removal sub-system studies are presented. System CO_2 removal capacity and air loss rate are evaluated using different operating process conditions and modifications in the mode of PED purge desorption. Finally, the application of the Heatless Desorption Process to Space Shuttle and Skylab missions are discussed in section 5.

2. HEATLESS DESORPTION FUNDAMENTALS

2.1 Heatless Desorption For Drying Processes

The basic Heatless Desorption process, as used in drying operations, is a cyclic, two, bed, pressure-swing process which utilizes a purge to assist desorption. Figure 1 shows a typical Heatless system in which two fixed beds of solid adsorbent material are alternately cycled between adsorption and desorption.

Figure 1

BASIC HEATLESS DESORPTION SYSTEM

Product

ADS.
(1)

DES.
(2)

Purge
Effluent

Feed

⊘ 4-way Valve

–K– Check Valve

⋈ Throttle Valve

— Gas Flow

— No Gas Flow
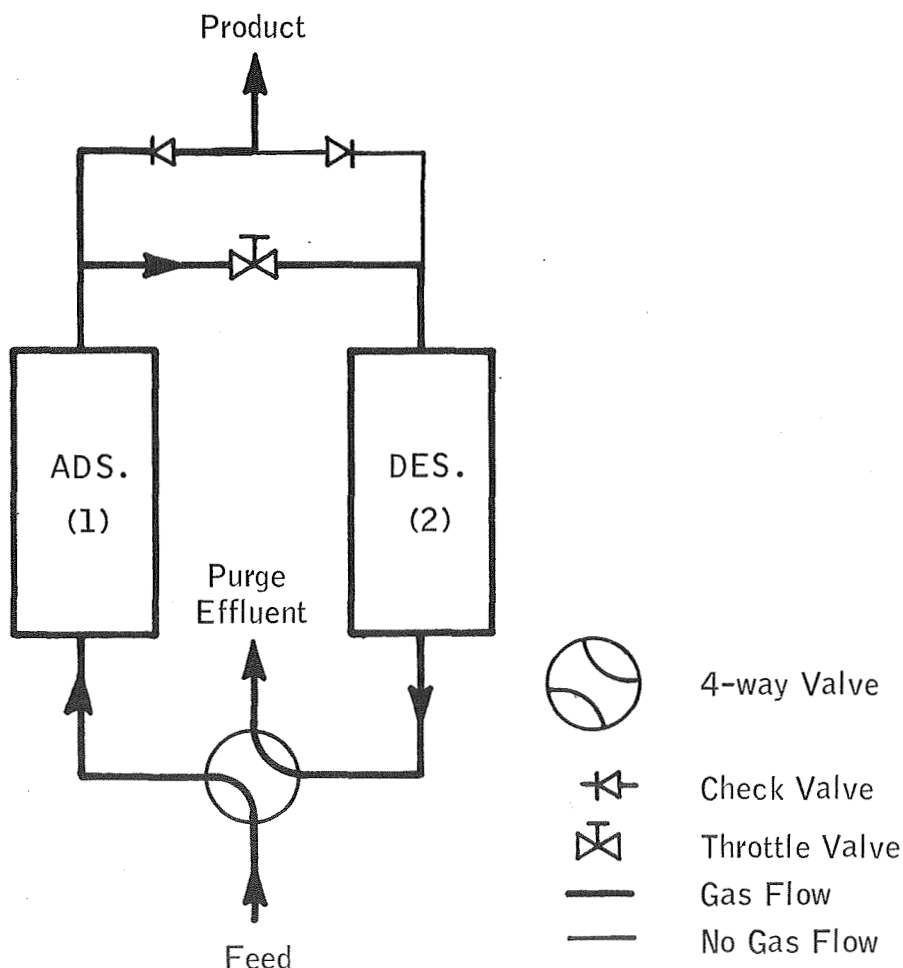
In the adsorption step (Bed 1), a feed stream is passed through the adsorption zone where specific components (e.g., H_2O and CO_2) are adsorbed. The effluent from this zone, free of these components, is split into two streams. One stream is available as product at feed pressure. The other stream is throttled to a lower pressure and used to purge the bed on desorption (Bed 2). Desorption results from the reduction in pressure and the sweeping action of the purge which leaves more concentrated with respect to the adsorbate than is the entering feed. By using two beds of adsorbent, the feed and product system can be operated continuously even though each bed operates cyclically.

Unlike existing adsorption processes relying on large cyclic adsorbent capacity (and consequently relatively large adsorbent beds), Heatless Desorption makes use of a small cyclic adsorbent capacity. This capacity is multiplied several times, however, through the use of very short cycles. Some commercial Heatless Desorbers, for example, undergo complete cycles once every minute. The capacity of an adsorption system is:

$$\frac{\text{System Capacity}}{\text{Unit Time}} = \frac{\text{Bed Capacity}}{\text{Cycle}} \times \frac{\text{Number of Cycles}}{\text{Unit of Time}}$$

It has been experimentally shown that although a smaller fraction of the ultimate capacity of the desiccant is used as the cycling rate increases, the decrease in capacity is less than the increase in the cycling rate. Thus, the system capacity, which is the product of the two, increases. This permits the utilization of smaller, lighter weight beds of adsorbent than is possible in other cyclic processes.

Rapid cycling is made feasible by improving the desorption. This is achieved in two ways. First, with a properly selected cycle time, the heat generated during adsorption is largely retained within the bed, and heat is available to aid in the subsequent regeneration step. Thus the heat of desorption does not have to be externally supplied to the bed. This eliminates the need for heat exchange equipment, embedded heaters, etc. In addition, the temperature of the adsorbent deviates only slightly from an average value, the adsorbing bed is ready for adsorption at the start of the cycle. This eliminates the possibility of premature break-through of the adsorbate that can occur at the start of a thermally desorbed cycle if the bed has not been sufficiently cooled. Second, the use of a purge gas provides a convective action which removes the desorbed components from the adsorbent much more rapidly than with pressure swing regeneration which depends partly on the relatively slow gas diffusion mechanism.

The only specific requirement on the purge flow for a balanced Heatless Desorption cycle is that the volume flow in desorption be slightly greater than the volume flow of feed. (The reasons for this are detailed in Appendix 7.1). Even if achievable, a purge to feed ratio of 1:1 would not be desirable since it represents a theoretical limit which would require infinitely large beds. On the other hand, the use of large purge to feed ratios may also be undesirable since it requires a large pressure differential between adsorbing and desorbing beds and hence larger power requirements. In actual practice, a trade-off is possible between purge to feed ratio and the size of the adsorption beds. For most space missions, it is probably better to design for minimum power (minimum purge to feed ratio) conditions.

2.2 Purge Aided Vacuum Desorption
For CO_2 Removal

In the Heatless Desorption method, product loss may occur in two ways: One is as purge if the adsorbate is to be collected; the other occurs when depressuring the bed between the adsorption and desorption steps. This depressure loss results from gas trapped in the void spaces of the bed and from gas (O_2 and N_2 for example) which is adsorbed to some extent on the molecular sieve. These losses can be reduced by the use of two modifications in the basic mode of operation - Bed Pressure Equalization (BPE) and Pressure Equalization Depressurization (PED).

Depressure loss can be reduced by equalizing the pressure between the adsorption and desorption beds as shown in Figure 2. At the end of an adsorption cycle (Step 1, Figure 2), the adsorbing bed at the higher pressure is connected to the desorbing bed at the lower pressure (Step 2, Figure 2). After the pressures have equilibrated, the beds are cycled so that the functions of each are reversed (Step 3, Figure 2). Thus, when the bed previously on adsorption is finally depressured, the amount of gas lost is reduced by the amount transferred during the equalization step. Meanwhile, the desorbed bed is partially repressured in preparation for the next adsorption cycle.

The purge loss can be significantly reduced using a technique termed Pressure Equalization Depressuring (PED). This consists of using a portion of the bed void gas (less than half of which is lost even with pressure equalization) to provide the required purge. The process is shown schematically in Figure 2. After bed pressure equalization has been completed, some gas still remains in the void volume of the bed. Rather than depressuring this bed directly to space, it is first depressurized into an evacuated cylinder until the pressures in the bed and cylinder have equilibrated (Step 3, Figure 2). The bed is then completely depressurized to its final desorption pressure, and the gas in the cylinder is then used at a controlled rate to purge desorb the bed further. (Step 4, Figure 2). By controlling the rate at which the PED cylinder empties (i.e., with a pre-set throttle valve. The purge can be used throughout all of the desorption cycle. By the end of the cycle, the cylinder has been evacuated and is once again ready to receive depressure gas from the other bed.

The benefit of PED if the adsorbate is not to be collected is that it provides a purge stream at no additional expense of product. In turn, the use of purge provides for more effective desorption and, hence, permits the use of smaller adsorbent beds with correspondingly smaller depressure losses. On the other hand, the depressure cylinder

Figure 2

PED UTILIZES VOID AIR LOSS FOR PURGE

STEP 1
Product

ADS.   Purge Cylinder Depress.   DES.

Purge Effluent

Feed
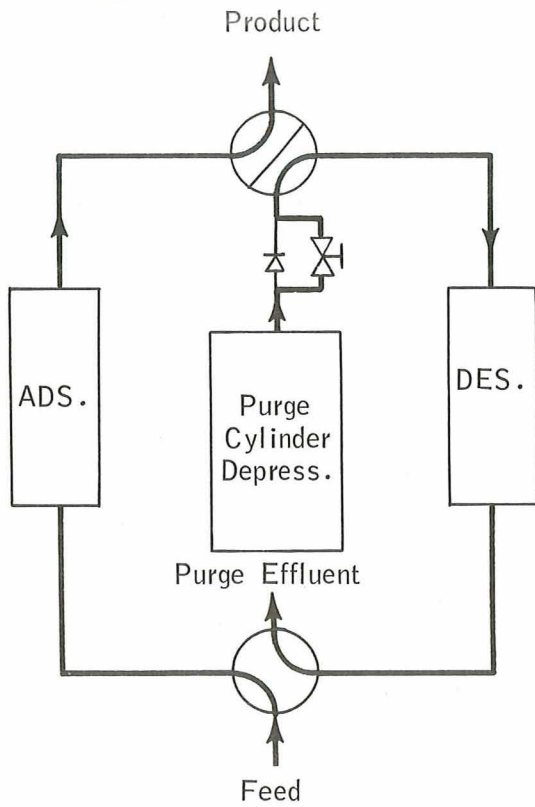
STEP 2
Bed Pressure Equalization

STEP 3
Pressure Equalization Depressuring

Purge Cylinder Repress.

STEP 4
Product

DES.   Purge Cylinder Depress.   ADS.

Purge Effluent

Feed
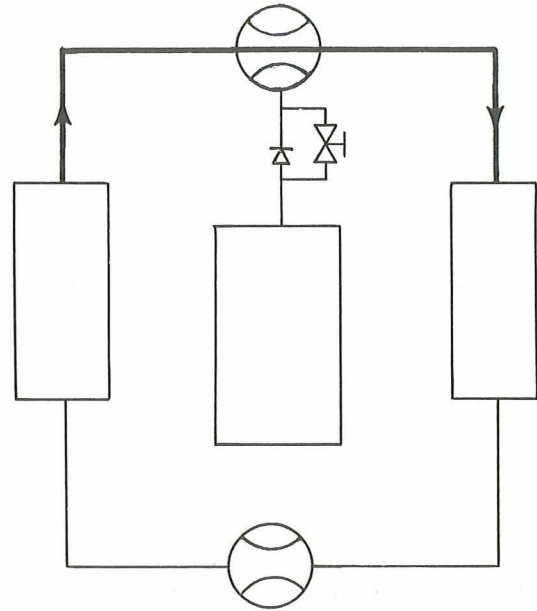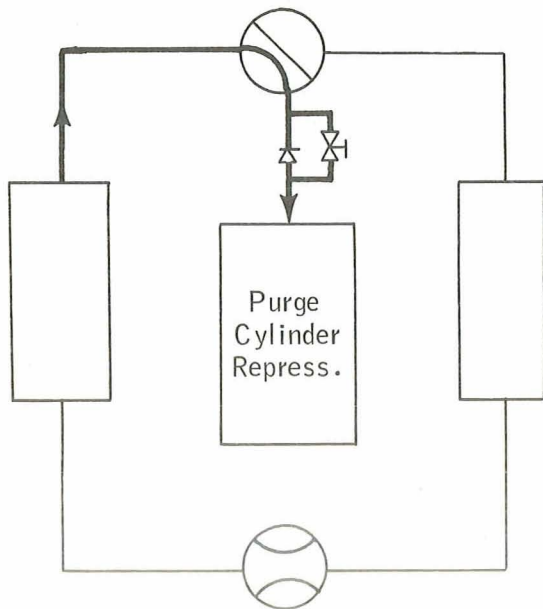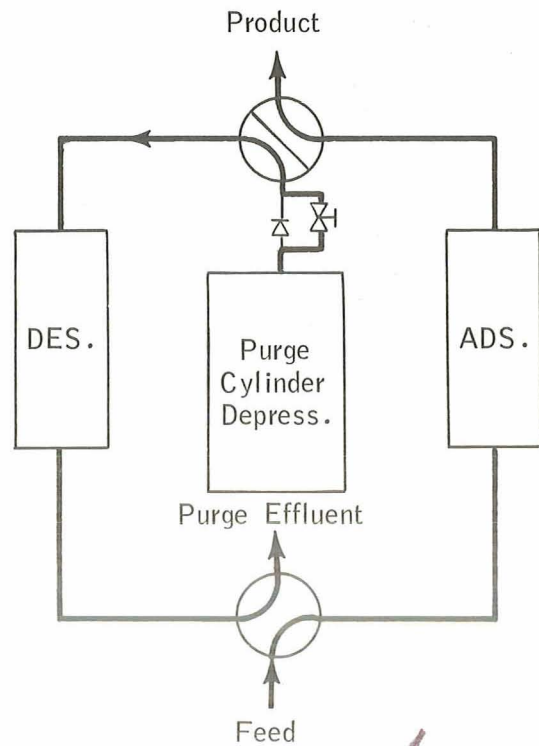
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adds a fixed amount of weight to the system, and the cycle becomes more complex. The size of the cylinder is proportional to the amount of purge desired. Thus, in a spacecraft system, for example, where overall weight is an important consideration, the reduction in the weight of the adsorbing beds and the decrease in product (air) loss derived from pressure equalization depressurization must be compared with the increase due to the added depressure cylinder. For long duration missions, the air loss rate becomes controlling and the added weight associated with PED may be acceptable. For shorter missions, however, this may not be so.

Although the Heatless Desorption technique has already been utilized in several commercial separation processes, its possible application to the removal of contaminants (such as carbon dioxide) from spacecraft atmospheres has only recently been investigated in NAS 1-6918 and the present contract. A schematic representation of the system which was studied under these Contracts is shown in Figure 3. This system was designed for use in that particular mode of operation in which carbon dioxide is removed and rejected to space while water is conserved and returned to the cabin.

The process itself consists of withdrawing cabin air down stream of a temperature-humidity control system. Such a system is needed to maintain a habitable environment in the spacecraft, and provides a process gas relatively low in pH_2O for use in the CO_2 control system. Process air from the dehumidifier enters the adsorbing desiccant bed at a dew point of from 40 to 50°F and with a CO_2 partial pressure depending on habitability criteria. The "dry" product from the desiccant bed enters the adsorbing molecular sieve bed where carbon dioxide is selectively removed. If a portion of the CO_2-lean effluent is to be used as purge for regenerating the desorbing molecular sieve bed, it is removed as a side stream. The desorbate, rich in CO_2, is rejected to space vacuum. The remainder of the CO_2-lean gas is throttled to a lower pressure and used as a purge for the desiccant before it is returned to the spacecraft cabin. In this way, none of the moisture removed during the drying step is lost. A throttle valve insures that the desired volumetric purge to feed ratio is maintained in the dryer. Figure 3 shows the system using the Pressure Equalization Depressuring technique for purging the desorbing CO_2 bed. This system was employed exclusively in the studies covered in this report (NAS 1-9356).

The processes outlined above incorporate Heatless Desorption techniques into both parts of the CO_2 control system. In the dryer, total product (after removal of CO_2) is used as a purge to aid the desorption of the dessicant. Cycle times as short as 30 to 60 seconds are employed to minimize bed temperature rise. The heat of adsorption/ desorption dictates the cycle time. In the CO_2 removal part of the

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Figure 3

COMBINED HEATLESS DRYING & CO_2 REMOVAL
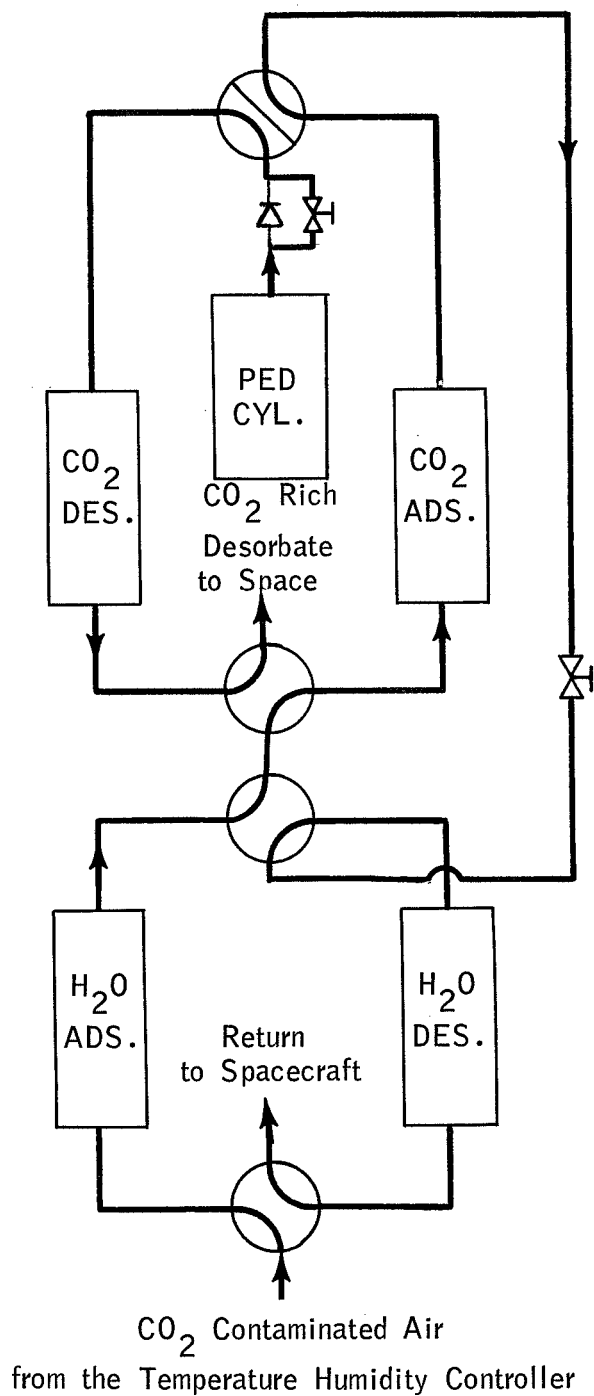
system, longer cycle times (e.g., 10 minutes) are desirable to limit air loss through too frequent depressurings. Alternate modes of coupling heatless drying and CO_2 removal systems are discussed in Section 5 of this report.

For the process shown in Figure 3, the only power requirements would be for the fan required to make up the pressure drop through the system. There would be no need to use electric power to heat the beds or to circulate heating fluid for regenerating the desiccant. Interstage cooling between the silica gel and molecular sieve beds would remain at the same average level during both the adsorption and desorption halves of a cycle.

The use of the described four-bed system permitted a logical separation of the experimental program into two phases since the drying and CO_2 removal processes operate essentially independently of one another. The first phase of the program consisted of further evaluating Heatless Desorption technology for desiccant regeneration. Specifically, two general areas were studied - 1) the performance of the silica gel system using very low purge to feed ratios and low space velocity conditions and 2) the performance of the dual zone silica gel-molecular sieve desiccant bed system. The Heatless Desorption drying sub-system studies are discussed in the next section of this report.

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3. DESICCANT SUB-SYSTEM INVESTIGATION

In this section the results of the investigation of the drying sub-system design parameters are discussed, and the experimental equipment employed in these studies is described. Low purge to feed ratios, low space velocity conditions, and bed performance with two sorbers were examined.

3.1 Desiccant System Performance Parameters

In the first study conducted in 1966 (Contract NAS 1-6918) an equation (response surface) was developed expressing the Heatless Desorption desiccant capability as a function of purge to feed ratio, space velocity and bed length. Using a statistically designed set of experiments, these variables were found to be the most important in determining system performance. Other variables such as cycle time and adsorption temperature were found to have less effect.

In considering each of the important process variables, it is apparent that the level which is most beneficial (i.e. the dryness of the product air) would not necessarily be optimum from a weight and/or power standpoint.

In practice, a compromise, or trade-off must be made among the process variables affecting the dryness of the effluent air. The nature of this trade-off would depend on the type of mission required, i.e. whether it would be better to design for minimum power consumption (minimum purge to feed ratio) or minimum weight. In general, as mission duration increases, it is desirable to design for minimum power.

The drying system studies, conducted in the present contract, were primarily aimed at defining performance at low purge to feed, and low space velocity conditions.

3.2 Description of Experimental Equipment

Experimental work was carried out using the equipment setup shown schematically in Figure 4. All gas lines were of 3/8" stainless steel tubing connected by 3/8" Swagelok fittings. Gaseous feed to the system was indicated by two rotameters through which air and CO_2 were passed independently. The air stream was pre-dried to dew points below -90°F with a commercial Heatless Dryer (Gilbarco Model HF-200) and the CO_2 was dried by passing it through a 24 inch long silica gel bed. The required feed dew point (43-45°F) was obtained by bubbling the dry air stream through water in a 4" dia. x 18" glass saturator vessel maintained at 20 psig and 74°F $\pm$ 2°F. This "wet" air then entered a liquid trap similar in construction to the saturator in order to prevent entrained liquid water from entering the desiccant beds.

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The back pressure on the two separate gas streams (i.e., saturated air and dry CO_2) was maintained at 20 psig by two back pressure regulators. At the outlet of the regulators, the streams were blended and passed through a coil which could be cooled by an air conditioning unit.

The desiccant containers were constructed of 1-1/2" I.D. glass tubes which could be obtained in various standard lengths. This permitted visual monitoring of the conditions of the desiccant. A more detailed picture of the bed-construction is shown in Figure 5. The beds were packed with silica gel held in place by fine wire gauze at either end to provide a support for the desiccant and to prevent particle loss during the pressure swings. The remaining unused space at both ends of the beds was filled with stainless steel mesh. In addition to acting as a low pressure-drop filler, this mesh served to distribute the feed and purge streams uniformly over the entire bed cross-section.

System vacuum was provided by a Welch Model 405 "Duo-Seal" vacuum pump rated at 1.75 CFM. A cartesian manostat (Manostat Corporation, Style No. 8) was used to control desorption pressures. Bourdon spring vacuum gauges (0-30 in Hg vac) were used for pressure measurements with a rated precision of $\pm$ 0.25 in Hg (abs). A manually regulated needle valve provided the adjustable pressure drop between the adsorbing and desorbing beds needed to set the purge to feed ratio.

The dry product from the adsorbing bed was split into two streams. The larger stream, constituting about 80-90% of the total, was used as purge for the bed being regenerated. The remaining fraction of the dry product was sampled under vacuum by a diaphram pump (Neptune Dyna Pump-4k) and analyzed for moisture content (instrument).

The principal instrument used in determining the moisture content of the dried gas stream was the Cambridge Model 992 Industrial Dew Point Hygrometer. This instrument has the capability of measuring process gas dew points to -100°F. It utilizes a unique optical detection and temperature control system whereby an insulated mirror surface (which is bonded to a thermocouple) is chilled by a thermoelectric cooler. As the condensate forms on the mirror, the optical sensing bridge detects the change in light level that occurs when dew or frost forms on the mirror and develops a proportional control signal to the power supply. This proportional direct current to the thermoelectric cooler permits the mirror to continuously track the dew point and detect changes less than .1°F. Actual dew point temperature is measured by a thermistor in the mirror assembly.

Figure 4

EXPERIMENTAL SET-UP

As shown,
Bed 1 is on adsorption
and Bed 2 is on purge
desorption.
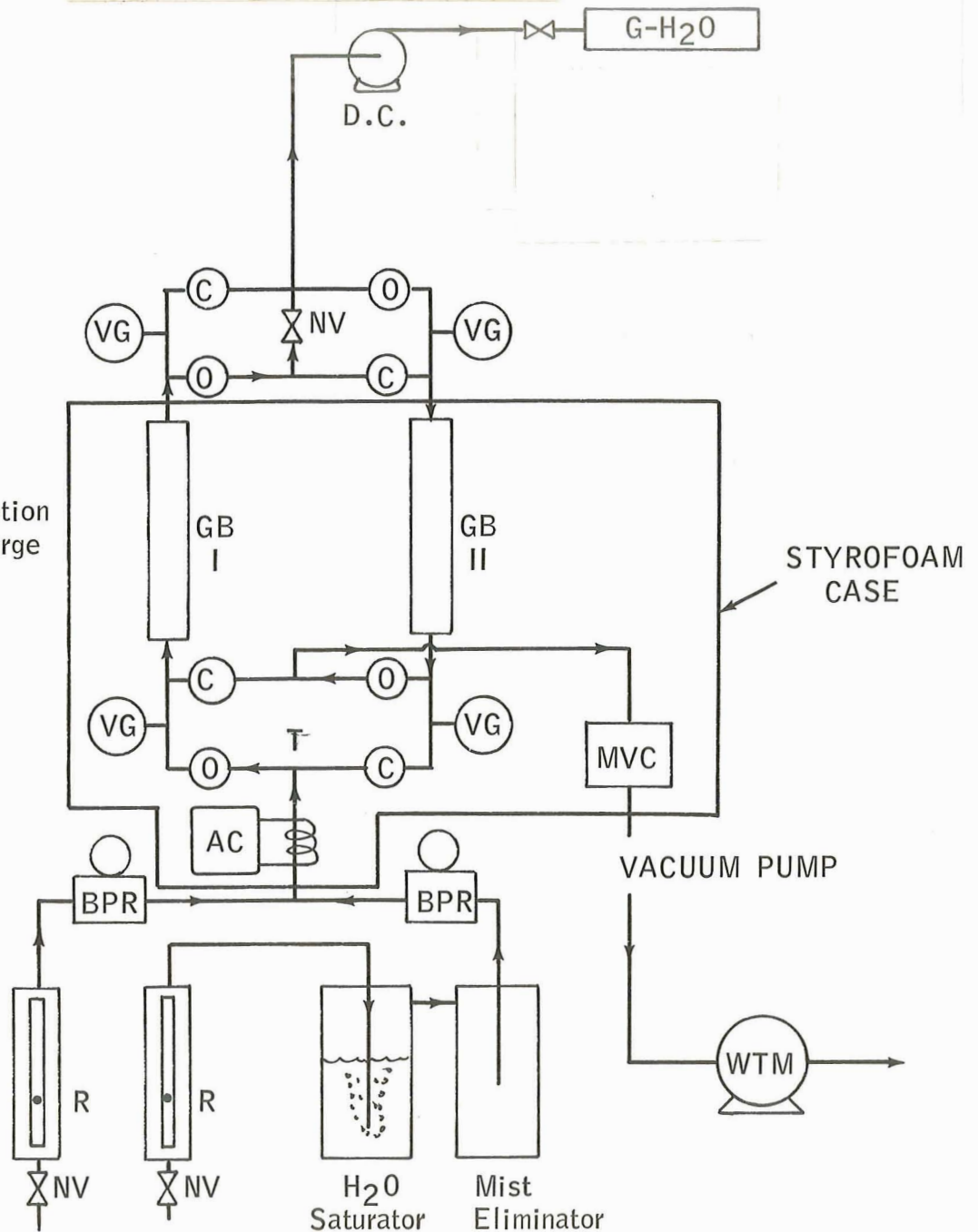
Symbols:

⊙ ⊙	= Open, closed solenoid valves	$G-H_2O$	= Cambridge Model 992 Hygrometer
NV	= Needle Valve	DC	= Diaphram Compressor
BPR	= Back pressure regulator	WTM	= Wet test meter
VG	= Vacuum Gauge	AC	= Air conditioner
GB	= Glass wallbeds, 1-1/2 ID	T	= Temperature point
MVC	= Manostat for vacuum control		
R	= Rotameter		

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Figure 5
DESICCANT BED CONSTRUCTION

OUTLET-3/8" S.S. Tubing

CYLINDER
GLASS RIM

METAL END
GASKETS

FINE
WIRE GAUZE

SILICA GEL

WIRE MESH

TEFLON "O" RING
GASKET

INLET-3/8" S.S. Tubing
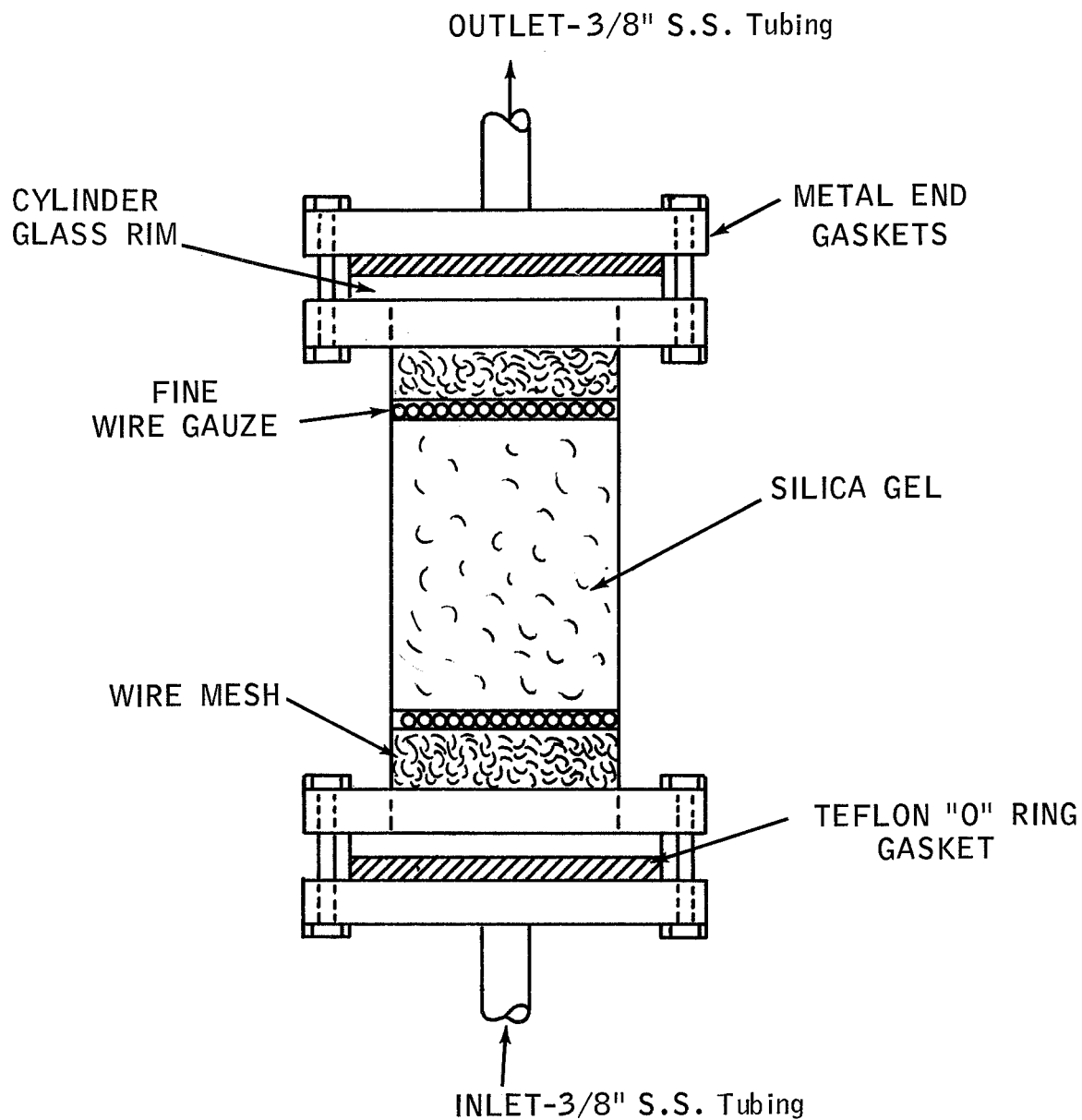
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The experiments required monitoring the water concentration in the dried effluent until a steady state condition had been achieved. This steady state level then represented the system response to the particular combination of variables used.

The unit was designed to operate continuously once the process variables had been set. For each run this involved setting the CO_2 and air flow rates, adjusting the automatic timer which activated the cycling valves, adjusting the purge to feed ratio by setting the pressures on the two beds.

Although the drying unit ran continuously around the clock, its operation was attended only during normal work day hours (less than 1/3 total operating time) and this involved only periodic adjustments in flow rates and bed pressures. In general, overnight variations for the former were less than 10% while the latter varied by no more than $\pm$ 0.5 in Hg. During the day, hourly readings were taken of effluent water concentration, inlet and outlet bed pressures, inlet gas temperature, saturator temperature, and ambient temperature. In addition, the moisture content of the feed gas was monitored periodically. This was done to provide a check on the operation of the saturator system.

Periodic shut-down of the unit became necessary as a result of system leaks, valve failures, and required mechanical changes (e.g., replacing beds). Actual time spent in diagnosing problems and subsequently eliminating them was less than 10% of the total available experimental time.

3.3 Typical Desiccant System Results

Figure 6 shows the typical response (product air water content vs. cycle time) that was obtained in the drying experiments. Each complete drying experiment took anywhere from one to 4 weeks to complete, and an additional day or two to dry the desiccant between runs. As used in this report, parts per million or ppm for short, is defined as $(P_{H_2O}/P \text{ atm}) \cdot 10^6$, where P_{H_2O} is the partial pressure of H_2O in the gas and P atm is atmospheric pressure. Reference to Appendix 7.2 will show that this is the most convenient way of representing the results.

Figure 6

TYPICAL RESPONSE FOR DRYING EXPERIMENTS
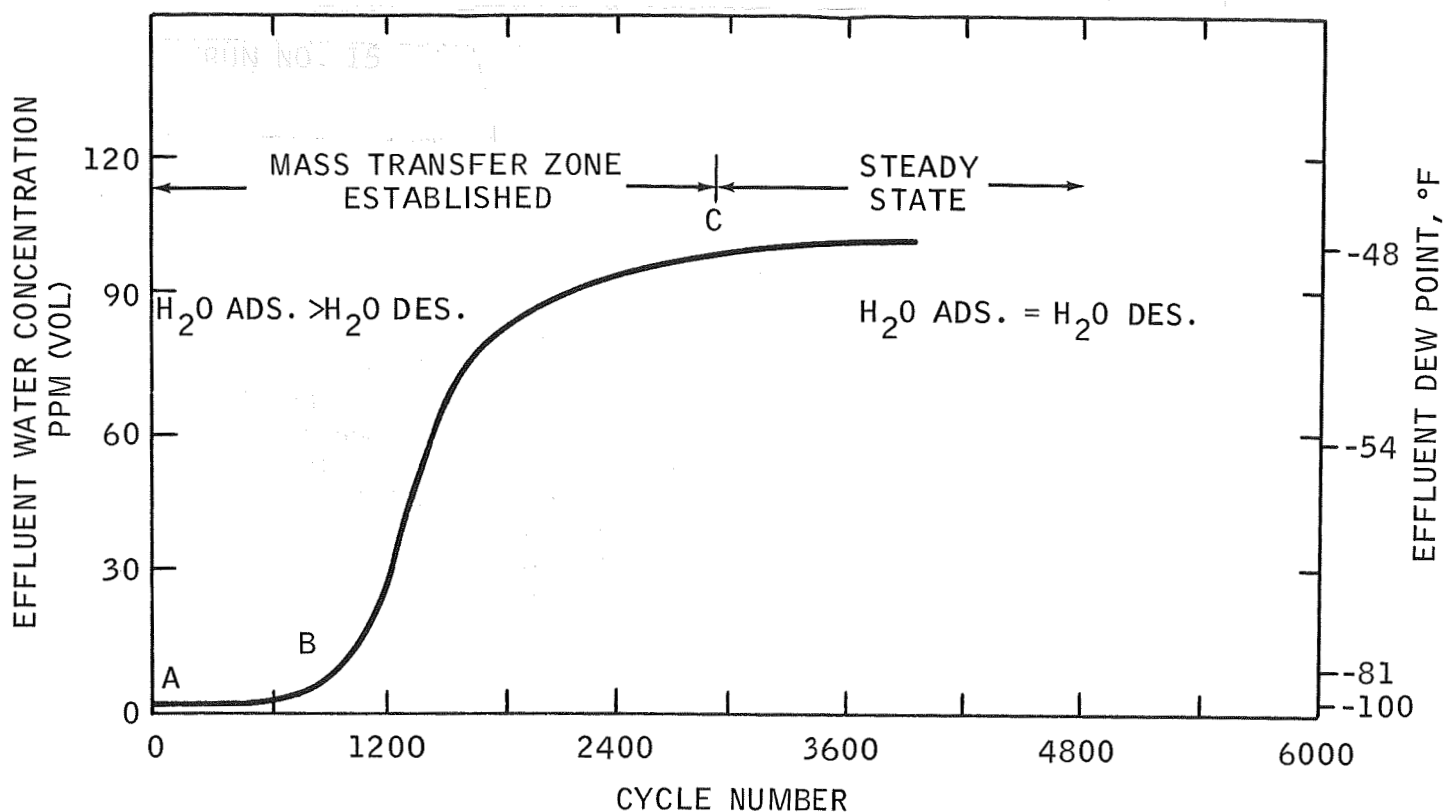
The shape of the drying response curve is characteristic of a Heatless Drying process. Since the cycles are short, change between alternate cycles are small. As cycling proceeds, the mositure content of the product increases from its initial level (Point A) to some final or steady state level (Point C) determined by the operating condition of that run. This steady state situation is reached when the mass transfer zone in the bed is sufficiently developed to saturate the purge to that level required for removing an amount of water equal to that brought into the bed during adsorption. In those cycles before the steady state is reached (Point B to Point C), the mass transfer zone in the bed is continually increasing since the amount of water desorbed is less than the amount adsorbed.

3.4 Performance at Low Purge to Feed and Low-Space Velocity Conditions

In the previous contract (Contract NAS 1-6918), drying studies examined performance at purge to feed ratios between 1.1 and 1.2 and at space velocities between 93 and 156 CFH/lb. of bed. A parametric design equation was developed based on data obtained from runs using the above range of conditions. This equation is given below:

$$\log \text{PFM } H_2O = 14.8612 - 12.5875 \text{ (P/F)} + 0.01113 \text{ (ft}^3/\text{hr-lb of bed)} - 0.1218 \text{ (BL, inches)}$$

In the present study, work was extended to cover performance at lower purge to feed ratios (< 1.10) and lower space velocities ($28-48 \text{ ft}^3/\text{hr-lb of bed}$). Since the power input to a heatless system is almost directly dependent on the purge to feed ratio, it is desirable to use as low a value as possible. It was hoped that a trade-off could be made between these two parameters to give effluent air water levels comparable to those obtained at high purge to feed, high space velocity conditions. In addition, we hoped to test the applicability of the parametric design equation to this range of conditions.

Single zone silica-gel bed performance, using low purge to feed ratios and low space velocities, was examined using 4" columns of Davidson Grade 40 silica-gel desiccant. Since half-cycle time and temperature were shown to have a relatively small affect on heatless drying system performance (see NASA report NO. CR-66852) they were fixed for the present study at 60 seconds and room temperature respectively. Runs were made at purge to feed ratios as low as 1.03 and space velocities ranging to 28 CFH/lb. of bed. The steady-state effluent air water concentration resulting from these runs is presented below in Table 2. The results of runs previously made at high space velocities and purge to feed ratios are also presented for comparison.

Table 2

Performance of Heatless Desorption Drying Unit

Run No.	Space Velocity ft³/hr-lb of bed	P/F	Steady-State Effluent H₂O Concentration in ppm	
			From Experiment	From Design Equation
D-17		1.10	4	2
D-18	28	1.05	8	7
D-20		1.03	250	30
D-16	48	1.14	4	5
D-15		1.12	16	10
D-14		1.03	512	77
D-8	156	1.21	14	7
D-9		1.08	412	350

(1) All runs made with a 4" column of Davidson Grade 40 silica-gel at a 1/2 cycle time of 60 seconds. Feed at a dew point of 50°F.

The results reported in Table 2 indicate that a trade-off can be made between space velocity and purge-to-feed ratios to yield comparable steady-state product water concentrations. A space velocity of only 28 ft^3/lb of bed and a purge-to-feed ratio of 1.05 is seen to give equivalent drying capacity to run with a space velocity of 156 ft^3/lb. of bed and a purge-to-feed ratio of 1.21. A similar trade-off can be made between runs D-16 and D-17.

Furthermore, effective drying can be realized at as low a purge to feed ratio as 1.03. Operation at this P/F would result in minimal power consumption. The drying equation, developed on Contract NAS 1-6918, was used to predict the performance of the heatless desorption drying runs presented in Table 2. Since this equation was developed using a minimum space velocity level of 94 ft^3/lb. of bed and purge-to-feed levels no lower than 1.10, we were interested in determining how well it predicted the performance of the low space velocity low purge-to-feed conditions used in the low P/F tests. As can be seen in Table 2, the effluent H$_2$O concentration predicted by the design equation agreed fairly well with the experimental data obtained with the exception of runs D-14 and D-20. Since the design equation appeared to hold up well for the space velocity and purge-to-feed levels of interest, it was used to help define the experimental conditions required to evaluate the two-zone silica-gel-molecular sieve bed approach. Two zone disiccant experiments are discussed in the following paragraphs.

3.5 Performance of the Two Zone Silica Gel-Molecular Sieve Desiccant Bed

Silica gel offers the best overall properties for use as a single desiccant in a Heatless Desorption drying system for manned spacecraft. Theoretical considerations, however, indicate that improved system performance should be possible if molecular sieves were to be used in addition to silica gel in two-zone desiccant beds. An explanation of the performance can best be made with reference to Figure 7 which shows the characteristic water adsorption isotherms for these two sorbents.

The isotherm of the molecular sieves, is very favorable at low pressure. However, in the flat portion of the isotherm (part B), heatless desorption of water from the sieve becomes very difficult since a large decrease in partial pressure ($P_2 \longrightarrow P_1$) effects only a small decrease in water loading ($L_2 \longrightarrow L_1$). With the relatively linear isotherm exhibited by silica gel, on the other hand, desorption is relatively easy since a decrease in pressure causes a proportional decrease in moisture loading. The silica gel has low capacity at low water vapor pressure. Consequently, a large part of a silica gel desiccant bed is needed to remove the last traces of moisture from the process gas.

/5 B

Figure 7

CHARACTERISTIC WATER ISOTHERMS FOR MOLECULAR SIEVE AND SILICA GEL

5A MOLECULAR SIEVE

SILICA GEL

H_2O CAPACITY OF SORBENT

H_2O PARTIAL PRESSURE
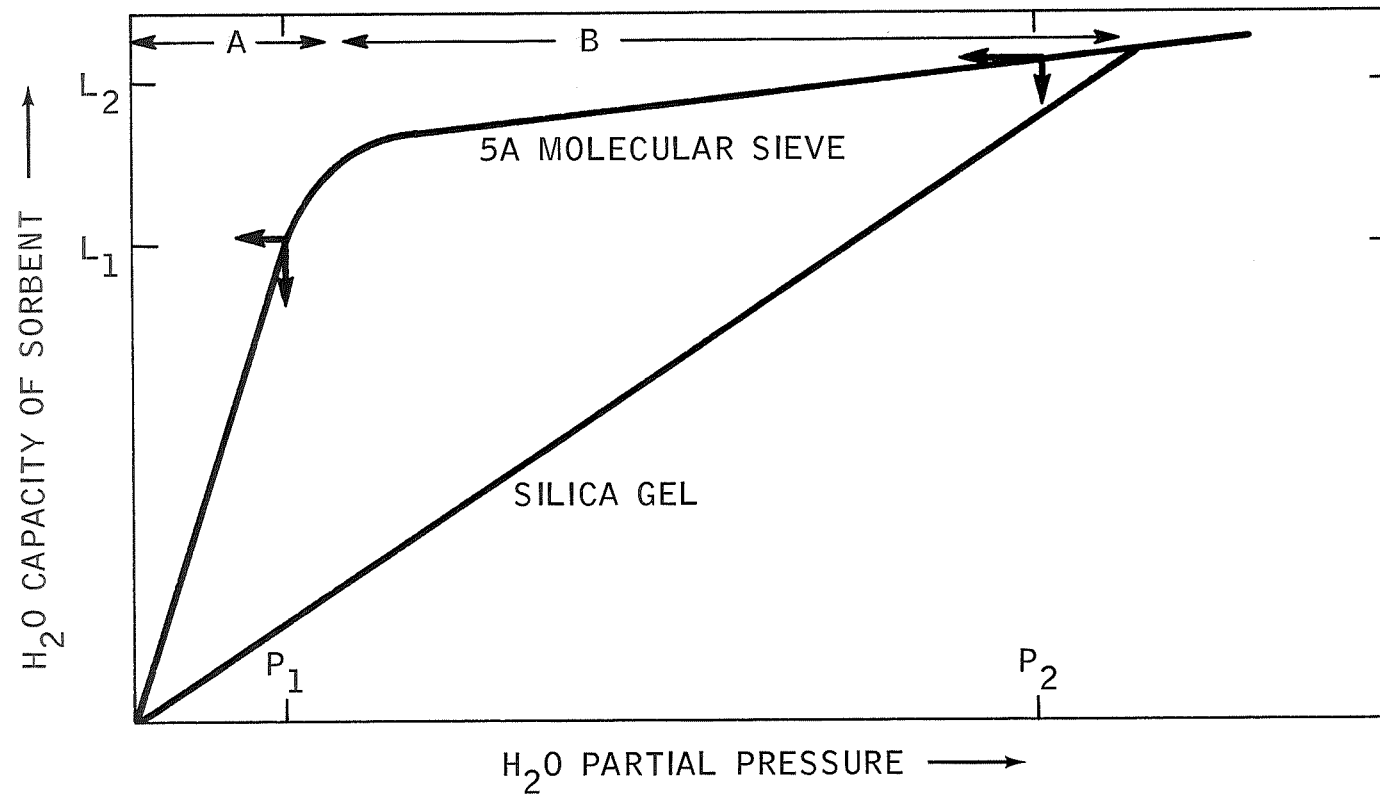
If we examine the isotherm for the molecular sieve more closely, we find that it can be considered being made-up of two regions which are shown in Figure 7 as A and B. At low pressure (region A), the isotherm is nearly linear. In this region, the sieve behaves like an ultra-high capacity silica gel in its desorption characteristics. Therefore, by keeping the water vapor pressure to which the sieve is exposed during adsorption below P_1, subsequent desorption by dry purge will be effective.

These properties of the silica gel and Molecular Sieve isotherms are exploited in the two-zone desiccant concept studied in this program. The desiccant beds in this concept each contain a zone of silica gel and a zone of Molecular Sieve. Moist gas first contacts the silica gel where the bulk of the moisture is removed to produce a partially dried gas whose water vapor pressure is within the linear portion of the molecular sieve isotherm (below P on Figure 7). Final moisture removal is then accomplished by the molecular sieve. Since the capacity of the sieve is higher than that of the silica gel in the low moisture range, less sieve is needed than the silica gel replaced.

Preliminary experiments were conducted to determine the optimum division of silica gel and molecular sieve in the bed. If too little silica gel was used, the moisture content to which the molecular sieve would be exposed would be too high to effect easy desorption (i.e., it will be in the horizontal portion of the isotherm). If too little sieve was used, on the other hand, the gas would not be dried adequately.

In actual practice, tests were started with a fixed length of silica gel leaving "dead volume" in the column for molecular sieve to be added after the desired effluent moisture level was obtained - below P_1, L_1 on the molecular sieve adsorption isotherm. Experiments were then conducted to determine the extent process air drying depends on the amount of Molecular Sieve added for specified low purge to feed, low space velocity process conditions. The results of these two zone desiccant bed runs, using both 5A and 13X Molecular Sieves are presented in Table 3.

Table 3

Performance of Heatless Desorption Two Zone Bed Drying Systems

Run. No.	Weight of Sieves Added gms/Bed	Space Velocity* ft^3/hr-lb of bed	P/F	Steady-State Effluent H_2O Concentration ppm
D-20	None	28	1.03	250
D-23	None	48	1.03	416
D-25	12.5 5A M.S.	38	1.03	342
D-27	12.5 13X M.S.	38	1.03	250
D-24	25.0 5A M.S.	32	1.03	20+
D-29	25.0 13X M.S.	32	1.03	30+

* Based on total charge (M.S. + silica gel) of bed.
** 50 gms of Silica gel used for each run.

The use of the two zone silica gel-Molecular Sieve desiccant beds reduced the steady-state effluent water concentration below that produced by the silica gel alone for comparable levels of space velocity and purge to feed ratio. Though the addition of 12.5 gms of both 5A and 13X Sieve to the base charge of 50 gms of silica gel gave only marginal improvement, the 25 gm sieve increment gave a dramatic improvement in drying efficiency. Since we are operating in the "knee" region of the Molecular Sieve adsorption isotherm system, drying efficiency would be expected to be sensitive to the amount of sieve added. Apparently, 25 gms of sieve, or a ratio of sieve to silica gel of 1/2, is sufficient to produce a substantial improvement over a single zone silica gel bed at these process conditions.

Performance of the 13X Molecular Sieve silica gel two zone system appears to be somewhat better than the 5A silica gel two zone system. The greater ease at which 13X sieves can be desorbed is believed to be the main reason for the higher performance of this system.

Some preliminary design calculations have been made using our two zone bed, low purge to feed ratio, low space velocity run data. Desiccant weight and blower power requirements for these runs are compared with a typical run at high space velocity-high purge to feed conditions.

Table 4

Heatless Desorption System Design

Design Basis - 3 man crew, air flow requirements 4 CFM/man, cabin pressure 10 psia.

Desiccant Required lbs.	Space* Velocity CFH/lb.	P/F	Compression Ratio Required	Blower Power Required	Effluent H_2O Concentration PPM
Two Zone Systems					
Silica Gel - 15 lbs. 13X M.S. - 3.8 lbs.	38+	1.03	1.05	18	250
Silica Gel - 15 lbs. 13X M.S. - 7.5 lbs.	32	1.03	1.05	18	20
Single Zone					
Silica Gel - 4.6 lbs.	156	1.10	1.12	30	67

* Based on Total Desiccant Charge

\+ Process flow is same for all three comparisons: 12 ft^3/min

The results, given in Table 4, indicate that a trade-off can be made between sorbent requirements and system power. The low P/F, low space velocity, two zone bed runs require considerably less power, though more sorbent to dry spacecraft air. Thus, the two zone bed design can be used to enhance the performance of the Heatless Desorption drying system, producing very dry air with very low power consumption and an increase in fixed bed weight.

3.6 Conclusions

Heatless Desorption drying experiments conducted during this past program indicate that a favorable operating process variable trade-off can be made between space velocity and purge to feed ratios to yield acceptable product water concentrations. Typically, a space velocity of only 28 ft.^{3}/lb. of bed and a purge-to-feed ratio of 1.05 gave equivalent drying capacity to a run with a space velocity of 156 ft.^{3}/lb. of bed and a purge to feed ratio of 1.21. From a practical standpoint, this means that a Heatless Desorption drying system could be designed to operate at very low power consumption with an increased fixed bed weight.

The parametric drying equation, developed on the previous contract, (NAS 1-6918) was found to accurately predict the performance of the Heatless Desorption drying unit down to a purge to feed ratio of 1.05 and a space velocity of 28 ft.^{3}/lb.

The use of a two zone Silica Gel Molecular Sieve Heatless Desorption drying system reduced the steady state effluent water concentration below that produced by Silica Gel alone for comparable levels of space velocity and purge to feed ratios. Performance was found to be dependent on the relative amounts of molecular sieve and silica gel used with a critical sieve to silica gel ratio required to obtain very dry air ($<$ 50 ppm H_2O) at low space velocities 28-48 ft.^{3}/lb. of bed and low purge to feed ratios. This behavior is probably a result of the knee shape of the Molecular Sieve-adsorption isotherm. The performance of the 13X Molecular Sieve-Silica Gel two zone system appeared to be slightly better than the 5A Molecular Sieve Silica Gel system. The greater ease at which 13X sieves can be desorbed is believed to be the main reason for this performance advantage.

Preliminary system design calculations, based on the performance of the two zone desiccant bed operation at low space velocity and low purge to feed ratios, indicate that about 18 watts of compressor power and 19 lbs of desiccant (15 lbs. 13X M.S. and 3.8 lbs. silica gel) are sufficient to dry spacecraft air (3 man crew) to 250 ppm. A sorbent loading of 22.5 lbs. (15 lbs. 13X M.S. and 7.5 lbs. of silica gel) at the same blower power consumption could dry the spacecraft air to 20 ppm.

4. CARBON DIOXIDE SUB-SYSTEM DEVELOPMENT

The previous contract showed that the use of Pressure Equalization Depressurization (PED) purge for CO_2 removal was effective and gave improved performance over conventional product purge. Consequently, the present program concentrated on studying this method of operation with particular emphasis placed on evaluating the following PED purge desorption system modifications:

- Sorbent filled PED Cylinder

- Larger Volume PED Cylinder

- Delayed PED Purge

- Heated PED Purge

In this section of the report, the important CO_2 system parameters, the experimental equipment, and the results of the above modifications are described and discussed.

4.1 System Parameters

In designing a CO_2-molecular sieve sorption system with PED aided desorption, three factors should be considered: system weight, air loss during desorption, and process gas flow rate. System weight will depend to a large extent on the amount of Molecular Sieve required and therefore the sorbent's cyclic capacity. The gas flow rate will be set by the CO_2 removal efficiency (i.e., fraction of CO_2 in the process gas that is adsorbed), and the CO_2 concentration in the gas. Process gas flow rate, together with system pressure drop, will determine the power required by the fan to move the process gas through the system. Finally, air loss during desorption will depend on the effectiveness of the purge desorption and the resultant cycle time and fixed bed size. The air loss comes from air trapped in the void spaces of the bed and from oxygen and nitrogen which are adsorbed by the molecular sieve.

The purpose of this investigation was to evaluate the effectiveness of PED purge desorption at different operating conditions. The system parameters that were considered important and were varied in this study were the sorbent, cycle time, and space velocity. Bed length, and CO_2 partial pressure were fixed during most of the runs. Table 5 shows the values of these parameters that were investigated.

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Table 5

Parameters Investigated for
Purge Desorption of CO_2

Operating Variables	Levels Investigated
Space Velocity	60, 130 and 180 $\dfrac{ft^3}{hr\text{-}lb}$
Cycle Time	5, 10, 20, 30, 60 Minutes
Molecular Sieve	Linde 5A and 13X, 1/16" Extruded pellets

The bed length was 9 inches resulting in a L/D of 6. CO_2 partial pressure was 4 mmHg.

Variations in the basic PED mode of purge desorption were studied including the use of a sorbent filled PED cylinder, increasing the volume of PED cylinders, delayed PED purge and heated PED purge.

4.2 Description of Experimental Equipment

A schematic diagram of the pilot unit used for the CO_2 removal studies is shown in Figure 8. As in the drying unit, all lines were made of 3/8" SS tubing connected by swage-lock fittings, and the beds were constructed of 1-1/2" glass pipe. The molecular sieves were held in these beds with stainless steel wire mesh packed firmly on both sides of the adsorbent.

The process gas was a mixture of CO_2 and air metered independently through two rotameters. The air stream was pre-dried to dew points below -90°F with a commercial Heatless Dryer (Gilbarco Model HF-200) and the CO_2 was dried by passing it through a 24-inch long silica gel bed. Back pressure was maintained at 20 psig with two back pressure regulators. The separate streams were blended in proper proportions to yield the desired flow rates and CO_2 partial pressures. The mixed stream was then fed to the bottom of the adsorbing bed. This bed was maintained at the adsorbing pressure (about 21.9 in Hg abs.) by means of a CENCO, Megavac, vacuum pump, Model 92003 (rated at 2 CFM free air capacity) and an Emil Greiner, Model 5, cartesian manostat.

PRINT BOTH SIDES

Figure 8

CO$_2$ SORPTION UNIT
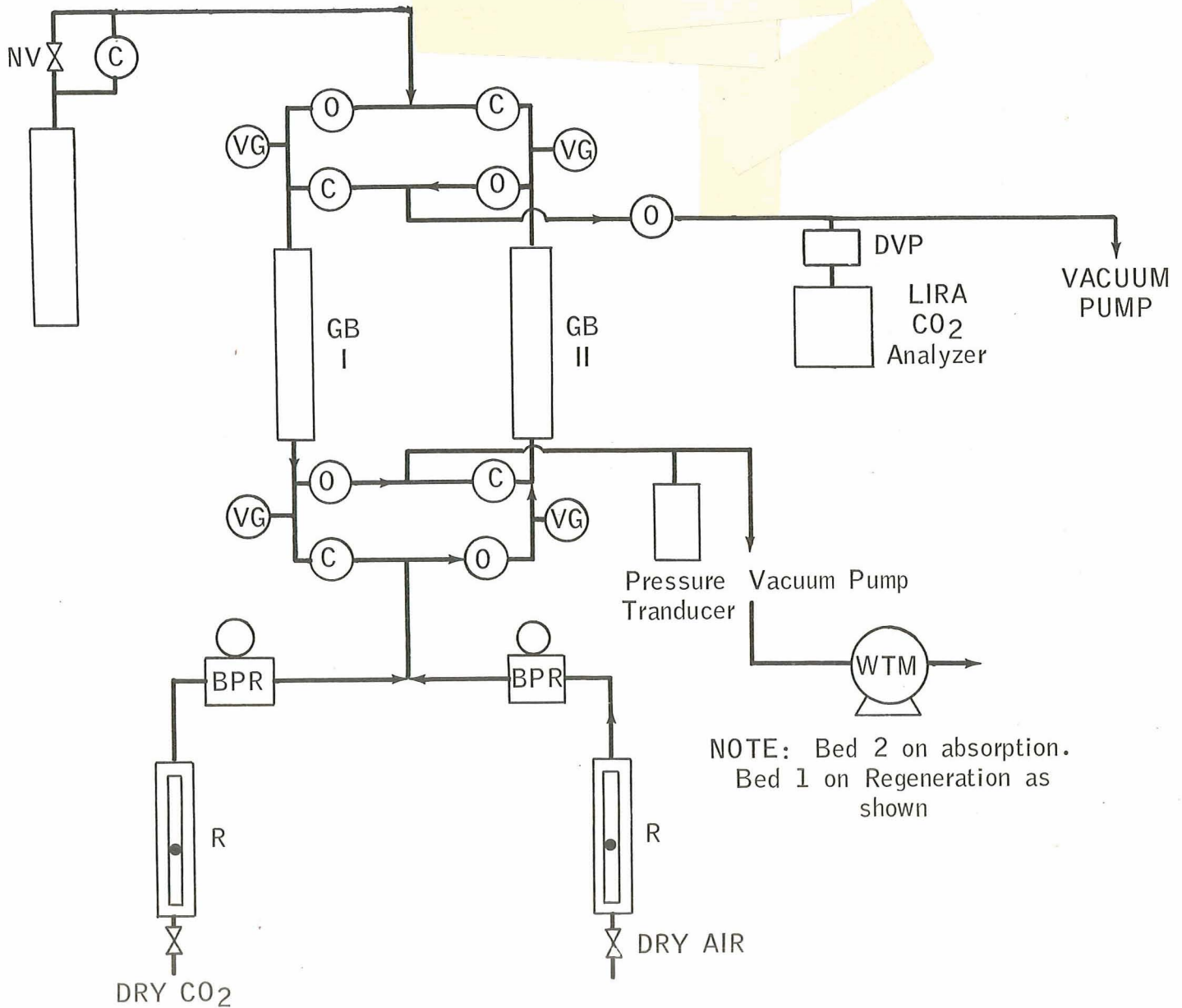
NOTE: Bed 2 on absorption.
Bed 1 on Regeneration as
shown

R   = Rotameter
NV = Needle valve
BPR = Back pressure regulator
VG = Bourdon vacuum gauges

DVP = Diaphragm vacuum pump
WTM = Wet test meter
ⓒ, ⓞ = Closed, open solenoid valves

197 OVER 12

Figure 9

PROGRAM CONTROLLED PROCESS SEQUENCE - CO_2 UNIT
10 MINUTE HALF CYCLE
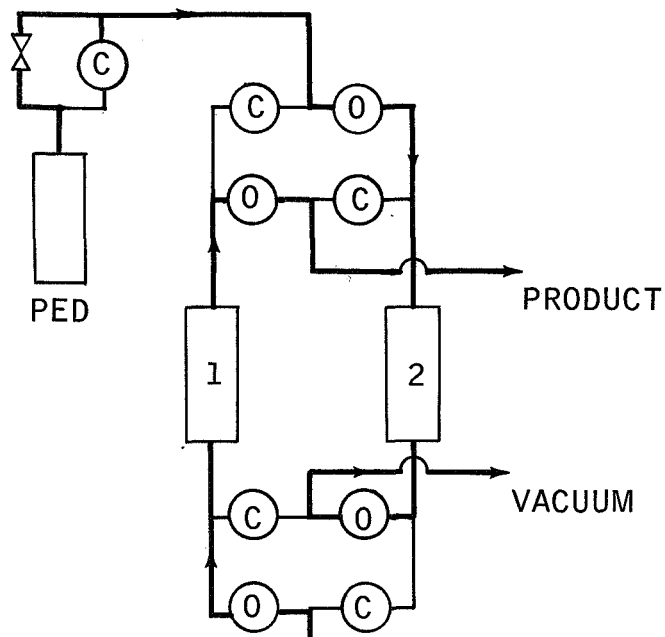
(a) BED 1 ON ADSORPTION (10 MIN.)
     BED 2 ON PED PURGE (10 MIN.)
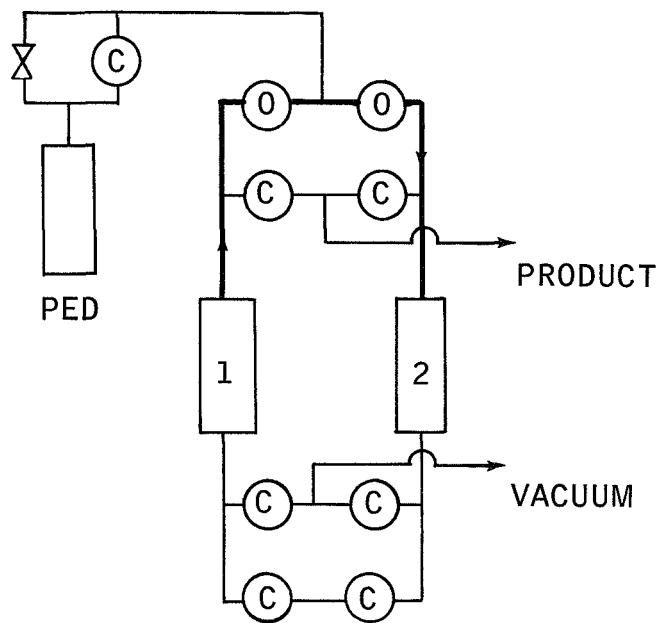
(b) BPE (10 SEC.)
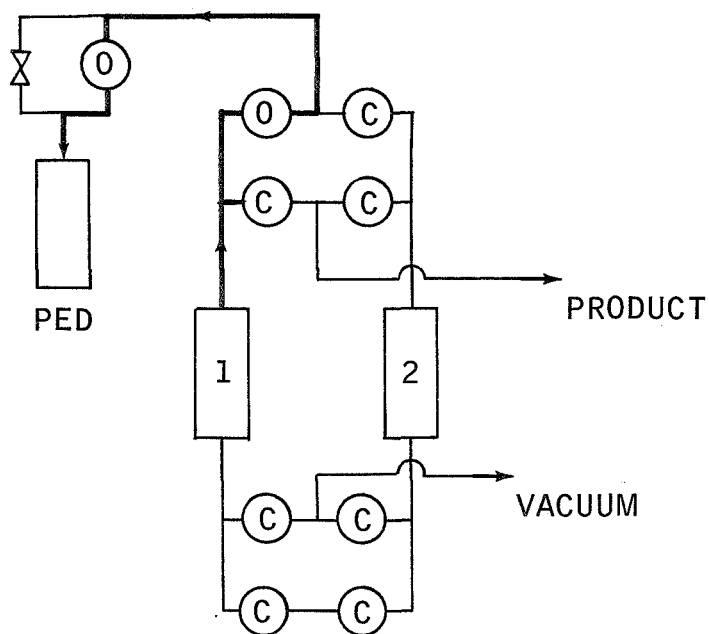
(c) PED (10 SEC.)
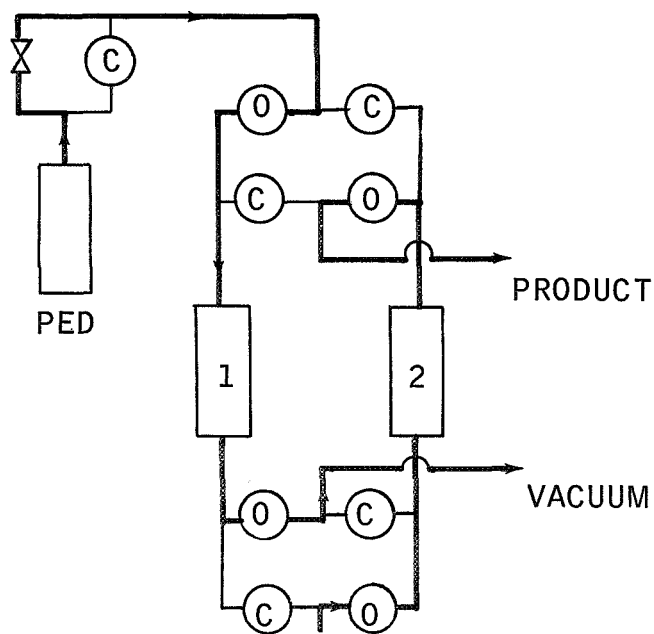
(d) BED 1 ON PED PURGE (10 MIN.)
     BED 2 ON ADSORPTION (10 MIN.)

$\textcircled{O}$ = OPEN SOLENOID VALVE
$\textcircled{C}$ = CLOSED SOLENOID VALVE

Desorption vacuum was provided by a Precision Scientific Model D-100 high vacuum pump (rated at 16.7 liters/sec pumping speed and on ultimate vacuum of 10^{-4} torr*. The pump was connected to the beds through approximately 5 feet of 1.5" line. Desorption pressure was measured at a point in this line located about 15" from the outlet of the beds with a Barocel 511 Pressure Transducer. The amount of desorbate was measured by a wet test meter connected to the discharge of the vacuum pump.

The Pressure Equalization Depressuring (PED) cylinders used ranged from .024-.142 ft.^{3} in volume. After bed pressure equalization, the adsorbing bed would be depressured into one of these evacuated cylinders through an Asco model 803041VM solenoid valve. After completing the PED step, this valve would be automatically closed and the gas in this cylinder used at a controlled rate (flow control valve) to purge the desorbing bed.

Automatic cycling was achieved throughout each step of the process using the same type of solenoid valves. These were activated sequentially by a cycle programmer manufactured by the Automatic Timer Corporation. This programmer was capable of independently activating any of ten solenoid valves in any part of the cycle. This allowed for maximum flexibility in operation. Figure 9 shows the valve sequence used for those runs utilizing the Pressure Equalization Depressuring purge technique.

Continuous sampling of the CO_2-lean product was carried out with a Neptune Dyna Diaphragm Pump (Model #3), and analysis of this sample was made by an infra-red CO_2 analyzer (Mine Safety Appliance, Model Lira 200). The same analyzer was also used for monitoring the feed CO_2 content. The signal from the CO_2 analyzer was continuously recorded on a Sargent Model 72150 Recorder. A typical recorded output is shown in Figure 13. The "saw-tooth" effect was obtained in all experiments and represents the breakthrough pattern of the system (i.e., the CO_2 concentration in the effluent from the adsorbing bed) while the upper solid horizontal line represents the CO_2 concentration of the feed. The area between the feed line and the product concentration curve indicates the amount of carbon dioxide removed per cycle. This was calculated for each run by graphical integration. A sample calculation is given in Appendix 7.3.

The CO_2 analyzer was calibrated daily since there was some tendency for the output signal to drift with time. Electronic problems with the analyzer were normally easy to detect and correct. On occassion, however, other malfunctions such as a faulty detecting cell were not as readily apparent, and these resulted in some loss of experimental time.

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* Initial adsorptions runs (A-1 to A-23) and all runs made on Contract NAS 1-6918 were made using a Cenco Model 91506 Hyvac 7 vacuum pump (rated at 2.79 CFM free air capacity and 1.24 CFM at 10^{-3} torr. This pump was connected to the beds through 5 feet of 3/8" line. The use of the higher vacuum pump and larger diameter connecting line to the adsorption beds resulted in a marked improvement in system performance. This improvement is discussed in ensuing paragraphs.

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Figure 10

TYPICAL LIRA OUTPUT

FEED PCO_2: ~ 4mm Hg

1/2 CYCLE TIME: 10 MIN.
FEED RATE: 139 CFH/LB
PURGE: PED
BED WT.: 0.4 lbs.
ADSORBENT: 5A M.S.

CO_2 PARTIAL PRESSURE, mm Hg

TIME, Minutes

- 28 -
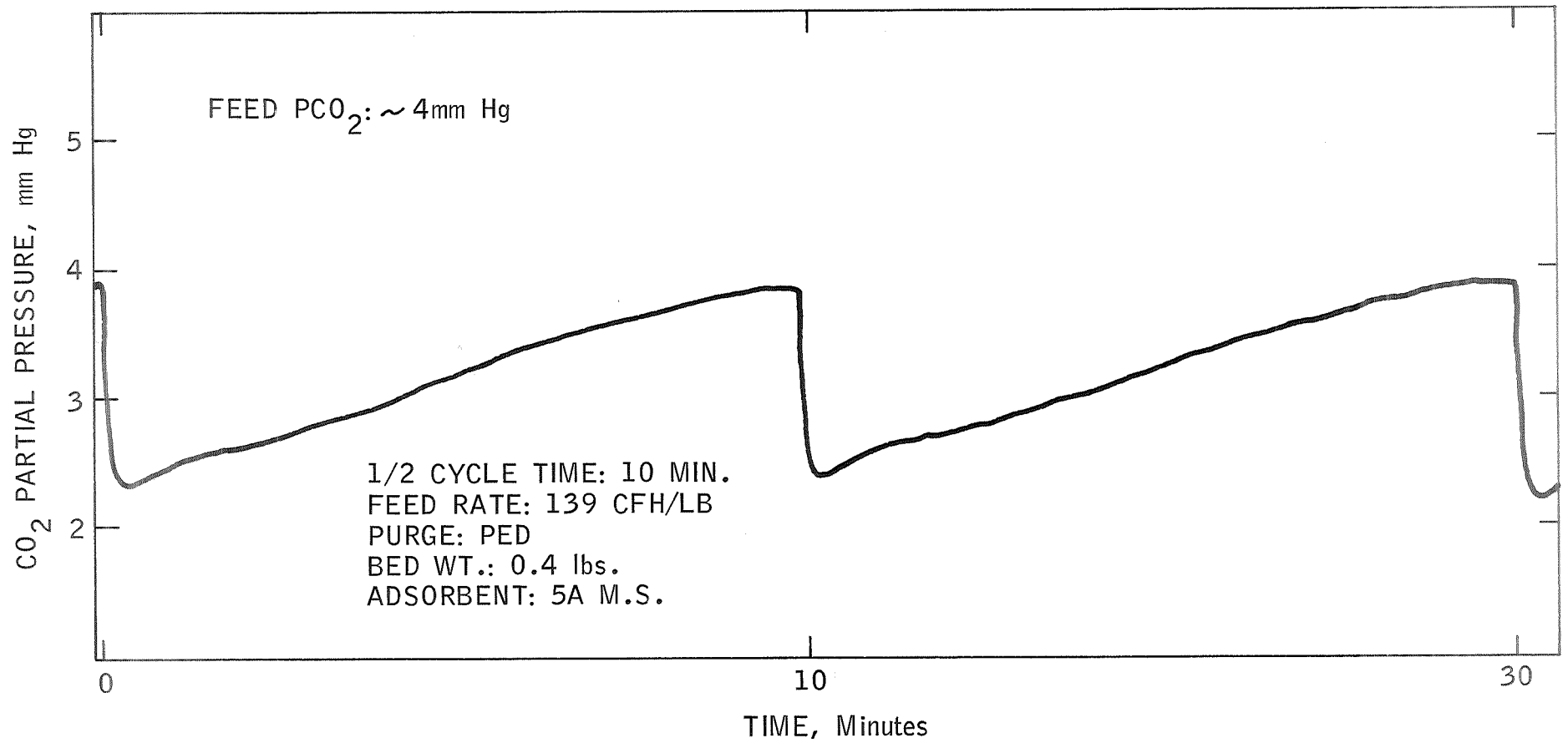
Having selected the set of operating conditions to be used in a particular run (i.e., space velocity, PED purge conditions, cycle time, adsorption pressure, and CO_2 feed concentration), the system was allowed to operate for three to four complete cycles prior to recording any data. In contrast to the drying experiments which required thousands of cycles, a few cycles were all that were needed for the CO_2 system to reach a steady state operation.

4.3 Effect of Improved Desorption Vacuum on System Performance

All CO_2 Heatless Desorption experimental work on NAS-1-6918 utilized a Cenco Model 91506 desorption vacuum pump (rated at .6 l/sec. at 10^{-3} torr) which was connected to the desorbing beds through 5 feet of 3/8" line. It was felt that the use of a higher capacity vacuum pump together with an increase in pump to adsorption bed connecting line diameter, would result in a higher ultimate vacuum in the bed undergoing desorption and hence, improved system performance. Accordingly, a new Precision Scientific vacuum pump (rated at 16.7 l/sec. pumping speed and ultimate vacuum of 10^{-4} torr) was installed in our test system and connected to the desorbing beds by means of 5 feet of 1.5" diameter line.

This new installation considerably reduced the ultimate vacuum in the sorbent bed during PED purge desorption as well as the time required to reach maximum vacuum. The net result of the use of the new pump was a substantial improvement in system CO_2 removal capacity as can be seen in Table 6 and Figure 11. The new pump installation was thus used to evaluate the effect of all system PED purge modifications as well as other process variable experiments.

The improvement in system capacity resulting from the higher system vacuum and pumping rate suggests that still further improvement may be possible with a lower desorption pressure. If the CO_2 desorption rates are such that the molecular sieve sorbent can be considered to be in equilibrium with the desorbing CO_2, the increase in capacity can be estimated by means of the adsorption isotherm for the system being used. Such an estimate indicates that only about another 10% increase in bed capacity would be realized if the desorption bed pressure was reduced to 10^{-2} torr. For a practical space application, the ultiamte vacuum and pumping rate seen by the sorbent beds will depend on the desorption line pressure drop i.e., design, types of valves used etc. The desorption bed vacuum anticipated for the AiResearch Skylab CO_2 removal system is about .5 torr.

4.4 Effect of Sorbent Filled PED Cylinder

The increase in capacity obtained by purging the sorbent during vacuum desorption depends, among other things, on the volume of purge used. One method of increasing the amount of purge for a fixed PED cylinder volume is to use a sorbent filled PED cylinder. Theoretically, for a fixed volume, a sorbent filled cylinder can hold more gas (O_2+N_2) at a given pressure than can be held by a cylinder of equal volume without the sieve. This can be seen in Table 7 which shows the respective theoretical amounts of gas held by an empty, and sorbent filled PED cylinder.

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Figure 11

EFFECT OF VACUUM PUMP
ON PED SYSTEM CAPACITY

PRECISION SCIENTIFIC MODEL D-1000
(16.7 liters/sec. pump speed at 10^{-4} torr)

CENCO MODEL 91506
(0.6 liters/sec. pump speed at 10^{-3} torr)

T = 73°F

SPACE VELOCITY 130 CFH/LB OF BED
5A MOL. SIEVE FILLED PED CYLINDER

BED CAPACITY, lbs. CO_2/hr.-lb. of Bed
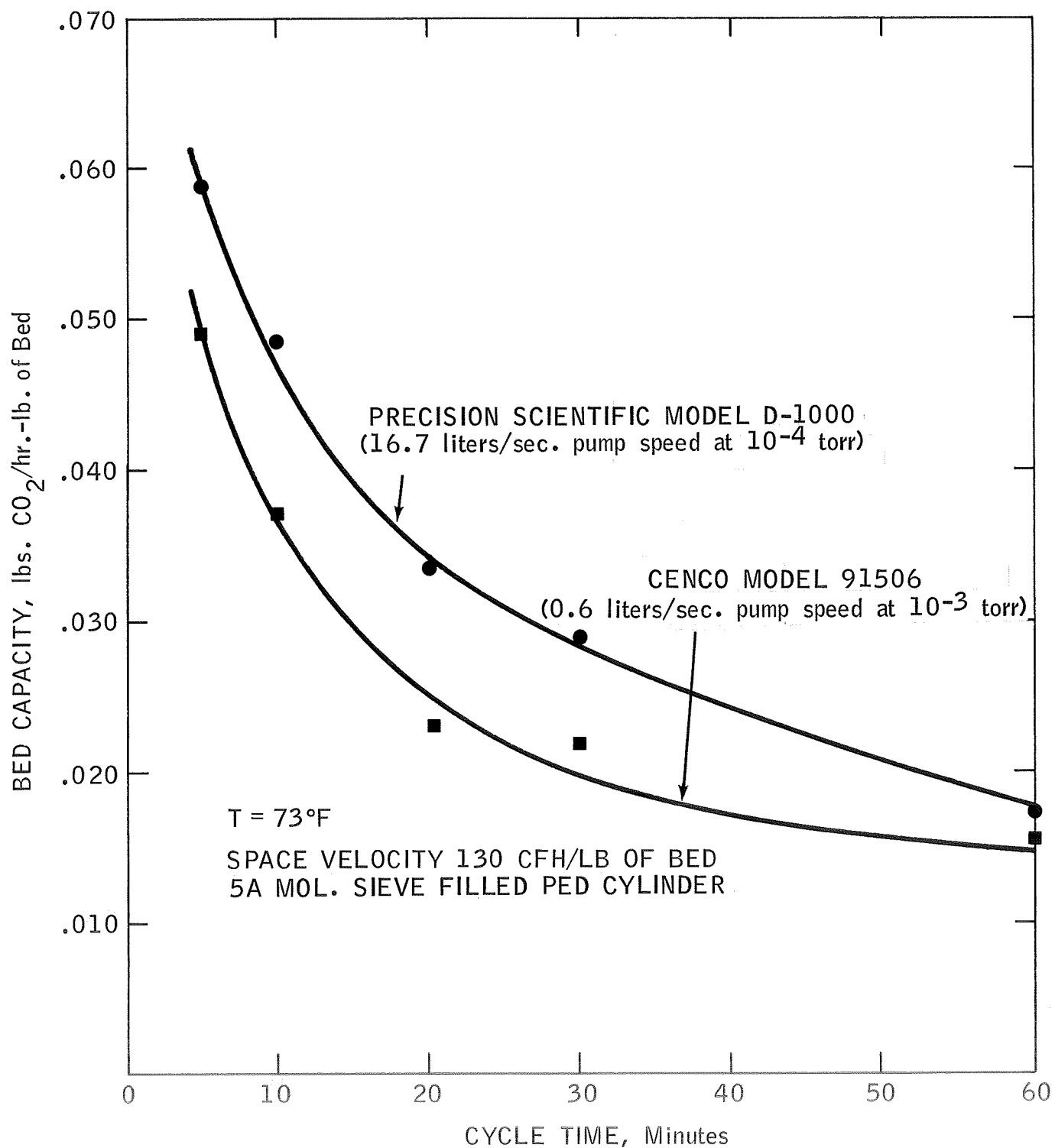
CYCLE TIME, Minutes

Table 6

Effect of Vacuum Pump Capacity
on Purge Desorption Performance

Run No.	Half Cycle Time, Mins.	Minimum Vacuum, mm Hg	Bed Capacity Lbs of CO_2 Hr-Lb of Bed	Air Loss Lbs of Air Lb of CO_2
A-15	5	2.3 (old pump)	0.049	0.65
A-27	5	0.84 (new pump)	0.059	0.65
A-14	10	1.8 (old pump)	0.037	0.39
A-32	10	0.68 (new pump)	0.047	0.34

Fixed conditions for all runs.

- PED cylinder filled with 430 gms of Linde 5A Molecular Sieve.

- Sorption columns filled with Linde 5A Molecular Sieve.

- 10 sec. bed pressure equalization, 10 sec. PED

- CO_2 partial pressure, 4.0-4.3 mm Hg.

- Adsorption pressure, 10-11 psia.

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Table 7

Purge Gas Capacity with Sorbent
Filled and Empty PED Cylinder (Theoretical)

Gas	Cylinder Without Sieve	Cylinder Loaded With 5A Sieve*	
O_2	.083 lbs	.165 lbs	.135 lbs adsorbed .030 lbs in gas phase
N_2	.073 lbs	.476 lbs	.45 lbs adsorbed .026 lbs in gas phase

- - - - -

* For 1/16 extruded 5A Sieve, the sorbent takes up only about
65% of the total volume. The remaining volume contains gas
phase O_2 or N_2.

Besides increasing capacity, the use of a sorbent filled de-
pressuring cylinder should provide one additional advantage. By using the
same sieve in the PED cylinder as used in the CO_2 sorbing beds, and
making its size approximately equal to these beds, the PED cylinder could
be used as a spare bed if one of the primary beds were to become de-
activated. This might permit an otherwise inoperative system to continue
functioning at a reduced capacity using conventional vacuum desorption
for sieve reactivation.

The sorbent filled PED cylinder concept was evaluated using a .024
ft.^{3} cylinder. Runs were made using both a Linde 5A Molecular Sieve filled
and a sorbent free PED cylinder under identical process conditions. Comparative
system performance was evaluated at different cycle times, and two different
space velocities using adsorption beds packed with Linde 5A Molecular Sieve.
The results are presented in Table 8 and Figures 15 and 16.

The test results surprisingly did not show any advantage in system
CO_2 removal capacity using the 5A Molecular Sieve sorbent-filled PED cylinder.
In fact, air loss rates appear to be somewhat greater for the runs made with
a sorbent filled PED cylinder. The most probable explanation for this result
may be the greater sensitivity of this technique on the vacuum pressure
capability of the system. Also, it may increase the time constant of the
desorption system. That is smaller beds and faster cycle time with an increase
in vacuum capability may be necessary to achieve increased capacity with this
method.

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Table 8

Performance of 5A Sorbent-Filled Vs. Empty
PED Cylinder Runs

Run No.	Space Velocity $\frac{ft^3}{Hr\text{-}Lb \text{ of Bed}}$	PED Cylinder Condition	1/2 Cycle Time, Mins	PED Desorbate Vol. SCFH	Bed Capacity $\frac{Lbs\ CO_2}{Hr\text{-}Lb\ Bed}$	Air Loss $\frac{Lbs\ of\ Air}{Lb\ of\ CO_2}$
54		Empty	5	0.200	0.0369	0.89
38		Filled	5	0.350	0.0356	1.35
53	60	Empty	10	0.200	0.0316	0.63
37		Filled	10	0.220	0.0344	0.64
51		Empty	20	0.140	0.0314	0.24
58		Filled	20	0.142	0.0314	0.27
50		Empty	30	0.110	0.0267	0.20
57		Filled	30	0.120	0.0280	0.18
46		Empty	5	0.350	0.0541	0.64
27		Filled	5	0.410	0.0590	0.65
45	130	Empty	10	0.230	0.0424	0.42
44		Empty	20	0.150	0.0349	0.22
28		Filled	20	0.170	0.0330	0.31
43		Empty	30	0.115	0.0290	0.14
30		Filled	30	0.125	0.0285	0.15

Fixed Conditions for All Runs.
* 10 sec. pressure equalization, 10 sec. PED.
* Feed CO_2 partial pressure 4 mm Hg.
* Adsorption pressure 10 psia.
* Temperature, 72°F.

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Figure 12

BED CAPACITY USING EMPTY
AND FULL PED CYLINDERS

■ 5A M.S. FULL PED CYLINDER

● EMPTY PED CYLINDER

ALL RUNS MADE AT A CONSTANT SPACE
VELOCITY OF 130 $\frac{ft^3}{hr.-lb. of bed}$

ALL RUNS USE 5A M.S. IN DESORPTION
COLUMNS.

CAPACITY, lbs. of CO_2/hr.-lb. of Bed

CYCLE TIME, Minutes

23B
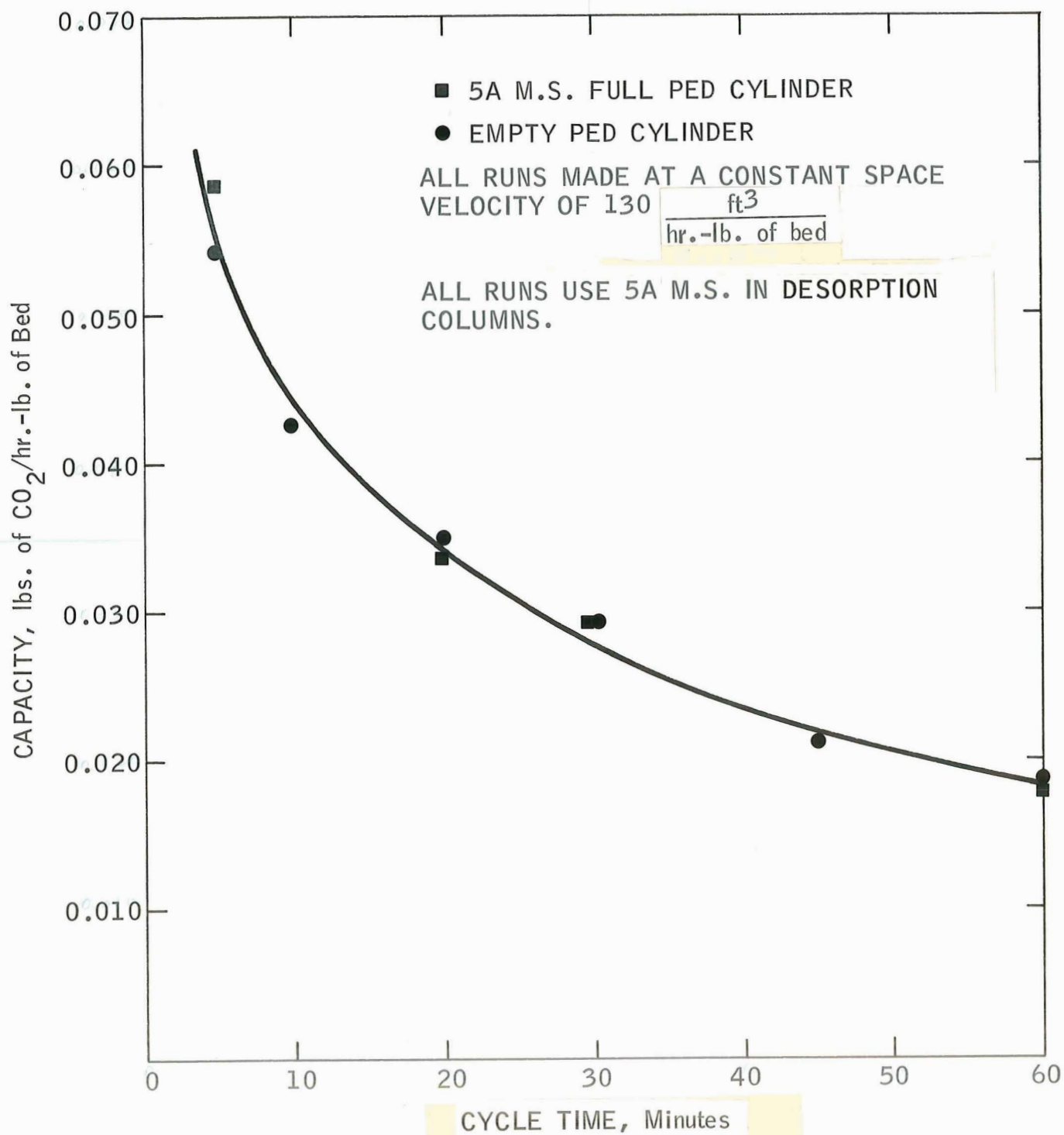
Figure 13

AIR LOSS RATE USING EMPTY
AND FULL PED CYLINDERS
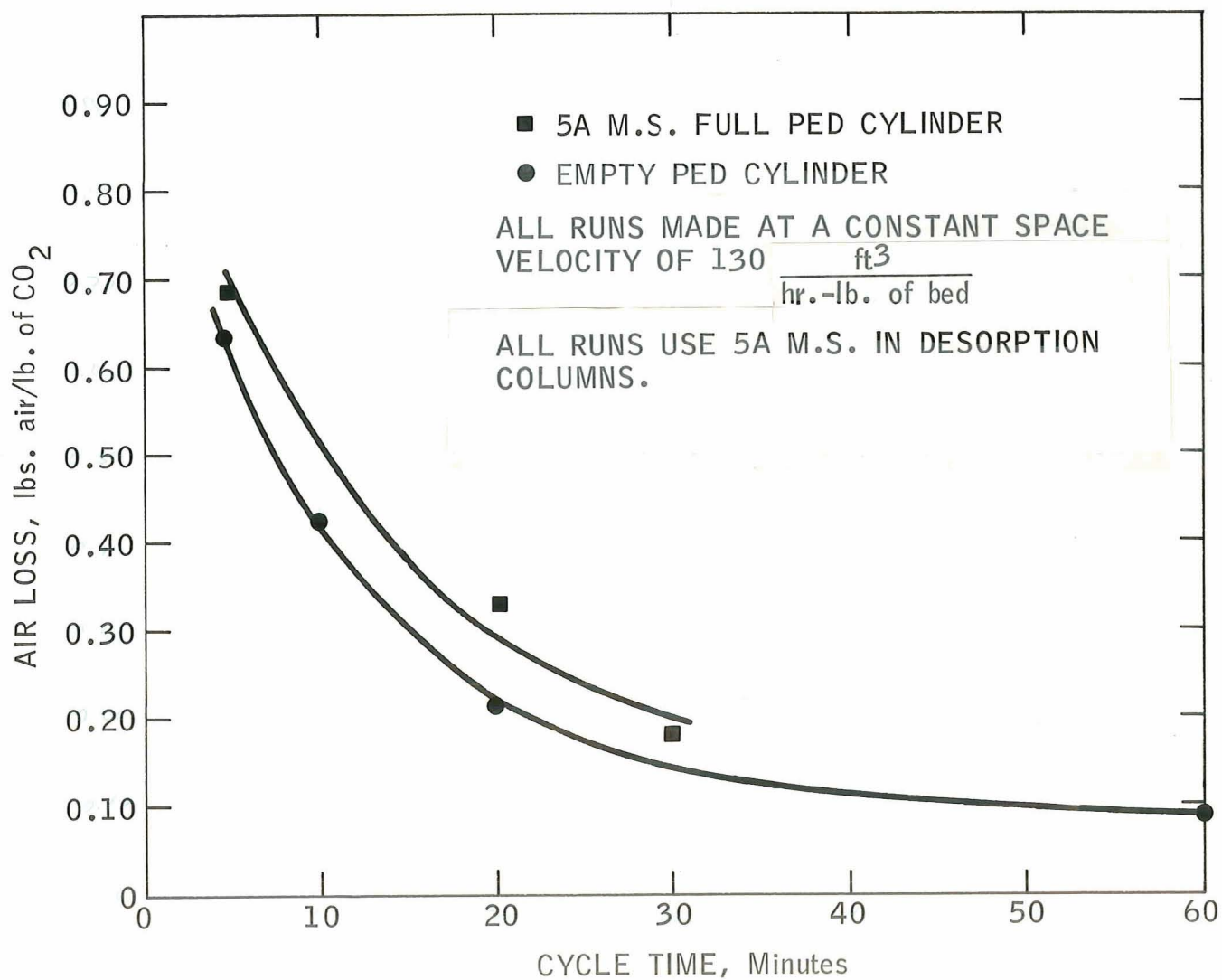
The sorbent filled PED cylinder concept might then be made effective if the adsorption bed geometry and system hardware were modified to give much lower pressure drop. The present system experimental hardware utilized adsorption columns with a very high L/D (about 6) and thus provided a high resistance for the desorption vacuum pump. Due to the limitations of time and the scope of the project, a re-evaluation of the sorbent filled PED cylinder concept with modified system hardware was not undertaken.

4.5 The Effect of Increasing PED Cylinder Volume

Another approach to improving the CO_2 removal capacity of the PED technique is through use of larger PED cylinders. Theoretically, increasing the volume of the PED cylinder should result in a higher purge flow and should increase the desorption. The availability of purge gas at a lower pressure at the beginning of desorption should result in more efficient removal of the adsorbed CO_2 and, thus, higher system capacity.

PED purge desorption runs were made with three different PED cylinders ranging from .024 to .142 ft.^{3} to test the feasibility of this approach. Space velocity was fixed at $130 \frac{ft^3}{hr.-lb \text{ of bed}}$ and the adsorption columns contained Linde 13X Molecular Sieve. (It is shown in subsequent paragraphs that the performance of both 5A and 13X Molecular Sieves are comparable). The results are presented in Table 9.

Table 9

Effect of Increased Cylinder Volume

Run No.	PED Cylinder Volume, ft^3	1/2 Cycle Time, Mins	Bed Capacity lbs Hr-1b of Bed	Air Loss Lbs of Air Lb of CO_2	Volume of Purge Desorbate SCFH
68	.024	10	0.0374	0.39	0.19
102	.071		0.0460	0.32	0.22
105	.142		0.0471	0.35	0.24
67	.024	20	0.0289	0.19	0.12
101	.071		0.0330	0.21	0.14
106	.142		0.0351	0.23	0.15

Fixed Conditions For Each Run:
- Feed CO_2 partial pressure - 4 mm Hg.
- Space velocity - 130 ft.^{3}/hr.-lb of bed
- Linde 13X Molecular Sieve
- Temperature - 72°F
- Adsorption pressure - 10.8 psia
- PED cylinder volume - 0.24 - .071 ft.^{3}

The use of larger (empty) PED cylinders is seen to effect a modest increase in system CO_2 removal capacity without incurring any appreciable increase in air loss rate. Increasing the PED cylinder volume by a factor of 3 results in about a 25% increase in system capacity at the 10 minute cycle and a 15% increase at the 20 minute cycle level. Further increase in PED cylinder volume to a factor of 6 relative to the base case, results in still higher system capacity but the incremental increase is lower.

At higher space velocities, the use of a larger PED cylinder volume has even a more pronounced effect. This can be seen in Table 10. Operation of the Heatless Desorption system at a space velocity of 180 CFH/lb of bed using a .071 ft.^{3} PED cylinder is seen to produce still further improvement in system capacity while reducing the air loss rate.

<u>Table 10</u>

Large PED Cylinder Tests-Effect of Space Velocity

Run No.	1/2 Cycle Time, Mins	Space Velocity ft^3/hr-lb	Bed Capacity lbs of CO_2 / hr-lb of bed	Air Loss lbs of air / lbs of CO_2
83	10	60	.0350	.50
87		130	.0498	.24
92		180	.0563	.18
80	20	60	.0280	.20
88		130	.0375	.12
93		180	.0399	.08

Fixed conditions for each run:

- Feed CO_2 partial pressure - 4 mm Hg
- 5A Molecular Sieve
- Adsorption pressure - 10.8 psia
- Temperature - 72°F
- PED cylinder volume - .071 ft.^{3}

It, thus, appears that the use of large PED cylinders can improve the performance of a vacuum Desorbed CO_2 removal system without incurring increased gas loss. This is accomplished by improving desorption efficiency and thus allowing longer cycle time.

In designing a flight system, a trade-off may be made in the volume and weight associated with the use of larger PED cylinders and the weight and volume of sorbent required. Also, such a trade-off would depend on specific mission requirements.

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4.6 Effect of Heated Purge

The desorption of carbon dioxide from molecular sieves becomes more favorable with increasing temperature. Thus, purge desorption could possibly be made more effective by increasing the purge temperature. Waste or electric heat could be used for this. In either case, there would be an increase in system weight because of the electrical heaters or heat exchangers that would be needed to warm the purge. Experiments were required to determine whether an improvement could be made in system performance through the use of a heated purge.

A tape heater was installed around the PED cylinder to provide a higher than room temperature purge. Runs were made using 5A sieve filled adsorption columns and a 5A sieve filled PED cylinder. Also, the sieve in the PED cylinder was expected to aid in the transfer of heat to the stored gas. The results of runs made using PED purge heated to 150°F are compared with conventional room temperature PED cylinder runs in Table 11.

Table 11

Performance of Heated Purge

Run No.	Half Cycle Time, Mins.	Purge Gas Temperature °F	Bed Capacity Lbs of CO_2 / Hr-Lb of Bed	Air Loss Lbs of Air / Lb of CO_2
A-60	10	150	0.0348	0.65
A-37	10	72	0.0344	0.64
A-59	20	150	0.0304	0.16
A-58	20	72	0.0314	0.27

Fixed Conditions For Each Run:
- Space velocity - 60 ft^3/hr-lb of bed.
- PED cylinder filled with 430 gms of Linde 5A molecular sieve.
- Adsorption columns each filled with 180 gms of Linde 5A molecular sieve.
- CO_2 feed partial pressure of 4 mm Hg.
- Adsorption columns at room temperature.

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As the test results indicate, no significant change in capacity was observed using PED purge heated to 150°F. In order for this technique to be effective, the heated purge gas must improve the desorption efficiency relative to the conventional cold purge. To do this, the heated purge must locally raise the molecular sieve bed temperature during the desorption step. The experimental results indicated that very little elevation in bed temperature took place during PED desorption, primarily because of the relatively large mass of the bed relative to the desorption gas used during the cycle. Only the first few layers of the bed experienced a rise in temperature, the purge gas being rapidly cooled to the temperature of the bulk of the bed. Because of this limitation, the heated PED purge approach did not seem practical and was not pursued further.

4.7   Effect of Delayed Purge

The most obvious way of improving purge aided desorption is to increase the purge gas volume by lowering the pressure for a given quantity of purge (i.e., moles). In either purge aided or conventional vacuum desorption of CO_2 to space, the desorption pressure does not remain constant; it continuously declines throughout the entire cycle as shown in Figure 14. Consequently, it would appear that the most effective way of using PED purge would be to delay its use until the desorption pressure had fallen to some predetermined low level. If this delay were too long, however, the desorption effectiveness might again decrease since the purge would be available then for only a short time. Thus, there may be an optimum purge delay time that would give the best overall desorption effectiveness. Also, air loss rates might be reduced using this technique by using the total amount of purge more effectively and allowing the cycle time to be increased.

Figure 14

DESORPTION PRESSURE TIME HISTORY
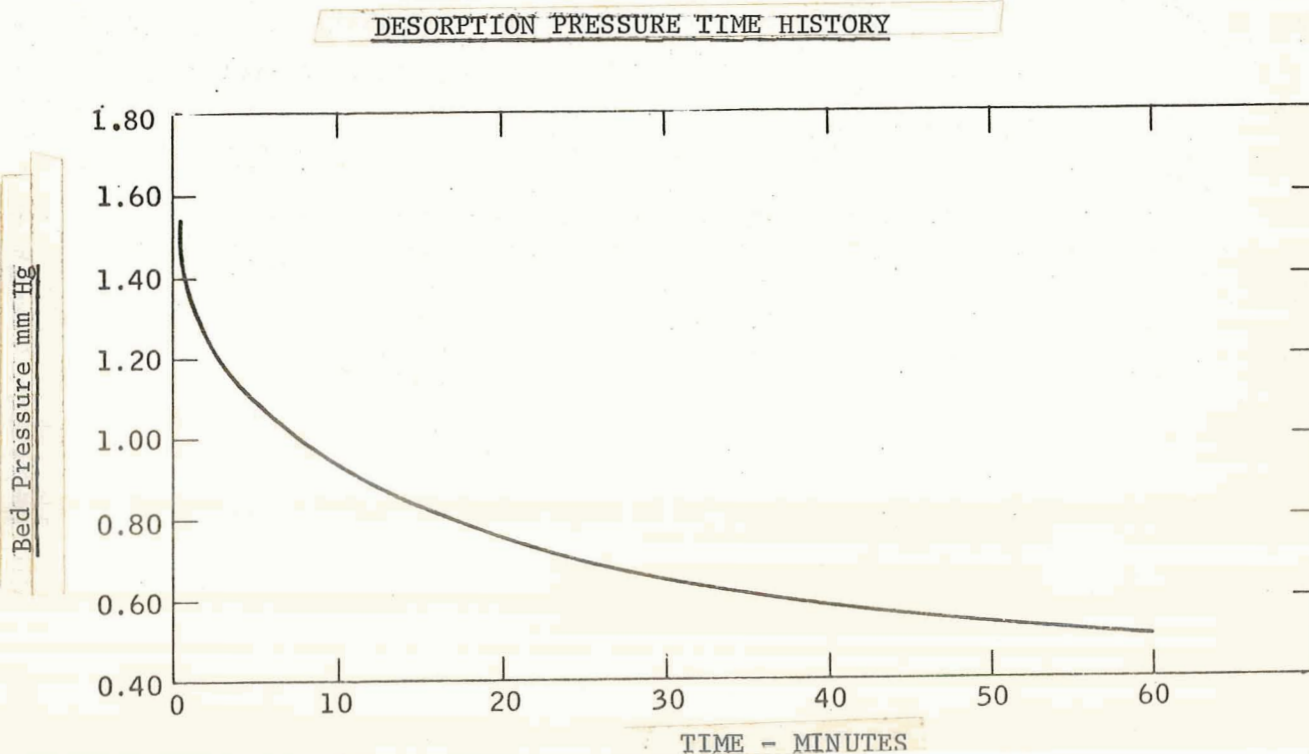
The delayed purge technique was evaluated using Linde 5A Molecular Sieve and a sorbent free PED cylinder (.142 ft^3). The results of these tests are given in Table 12.

Table 12

Effect of Delayed Purge

Run No.	1/2 Cycle Time, Mins	Purge Delay Mins.	Volume of Purge Desorbate SCFH	Bed Capacity lbs/hr-lb of Bed	Air Loss lbs of Air lb of CO_2
114	5	0	0.38	.0500	.90
124	5	0.5	0.37	.0495	.85
125	5	1	0.35	.0543	.66
112	20	0	0.16	.0341	.31
126	20	1	0.14	.0314	.27
127	20	2	0.14	.0333	.20
128	20	5	0.14	.0343	.19

Fixed conditions for all runs:
- Space velocity--130 ft^3/hr-lb of bed.
- Feed CO_2 partial pressure 4 mm Hg.
- Adsorption pressure of 10.8 psia.
- Temperature, 72°F.

Increased delay time in discharging the PED purge is seen to improve the air loss in both the 20 and 5 min. cycles. Though a 10 percent improvement in system capacity results from delaying the purge 1 min. in the 5 min. cycle, the capacity of the system during the 20 min. cycle appears to be virtually unaffected. Thus, on the basis of these results, the delayed purge technique appears to offer a relatively simple approach to reducing air loss rates in PED purge heatless desorption systems.

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4.8 Comparison of Type - 5A vs 13X Molecular Sieves

Both 5A and 13X type Molecular Sieves are effective in adsorbing CO_2. According to AiResearch Manufacturing Company, however, 13X sieve is believed to offer a distinct advantage because of both a greater ease in dynamically desorbing CO_2 and a lower tendency to co-adsorb nitrogen. Thus, comparative CO_2 performance tests were made in our Heatless Desorption CO_2 test unit using both 5A and 13X Molecular Sieve-filled adsorption columns. Runs were conducted at a fixed space velocity of 130 ft.^{3}/hr.-lb. of bed, using two different size (empty PED) cylinders, and two cycle times. The results are summarized in Table 13.

Table 13

Comparison of 5A and 13X Molecular Sieves

Run No.	PED Cylinder Volume ft^3	Sieve Type	1/2 Cycle Time mins.	Bed Capacity lbs CO_2 / hr-lb of bed	Air Loss lbs of air / lbs of CO_2
45	.024	Linde 5A	10	0.0424	0.42
68		Davidson 13X	10	0.0374	0.39
44	.024	Linde 5A	20	0.0349	0.22
67		Davidson 13X	20	0.0289	0.19
87	.071	Linde 5A	10	0.0496	0.24
102		Linde 13X	10	0.0465	0.32
96		Davidson 13X	10	0.0420	0.48
88	.071	Linde 5A	20	0.0375	0.12
101		Linde 13X	20	0.0331	0.21
97		Davidson 13X	20	0.0318	0.24

Fixed Conditions for all runs
- Space velocity - 130 ft^3/hr-lb of bed
- Feed CO_2 partial pressure 4 mm Hg
- Adsorption pressure 10.8 psia
- Temperature, 72°F

The runs made with either Linde or Davidson 13X Molecular Sieves are seen to be somewhat less effective in removing the CO_2 than those employing the 5A sieves. Thus, despite the more rapid desorption characteristics of the 13X sieves, they are not more effective in removing CO_2 with a pCO_2 of 4 mm Hg and purge desorption.

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4.9 Effect of CO_2 Feed Concentration

The possibility of operating molecular sieve carbon dioxide removal systems at a higher feed CO_2 partial pressure (by compressing the feed air) prompted the evaluation of the purge desorption technique at different CO_2 feed levels. Performance, as a function of CO_2 feed partial pressure, is given in Table 14 and Figure 15. Capacity is seen to increase markedly with increasing CO_2 feed partial pressure and air losses are substantially reduced. Thus, trade-offs can be made by increasing the feed partial pressure by means of a compressor.

Table 14

Effect of CO_2 Partial Pressure on the Performance of Purge Desorption

Run No.	CO_2 Partial Pressure in Feed, mm Hg	1/2 Cycle Time, Mins	Volume of Purge Desorbate SCFH	Bed Capacity lbs/hr-lb of Bed	Air Loss lbs of Air lb of CO_2
115	2.6	10	0.21	0.0240	1.12
113	4.0		0.24	0.0469	0.39
116	5.2		0.28	0.0582	0.31
117	6.8		0.35	0.0758	0.27
119	2.6	20	0.12	0.0233	0.42
112	4.0		0.16	0.0341	0.31
118	5.2		0.18	0.0465	0.12
120	6.8		0.21	0.0600	0.10

Fixed conditions for all runs:
- Space velocity - 130 ft^3/hr-lb of bed.
- Adsorption pressure of 10.8 psia.
- Temperature of 72°F.
- PED cylinder volume - .071 ft^3.

Figure 15

EFFECT OF CO_2 PARTIAL PRESSURE ON CAPACITY
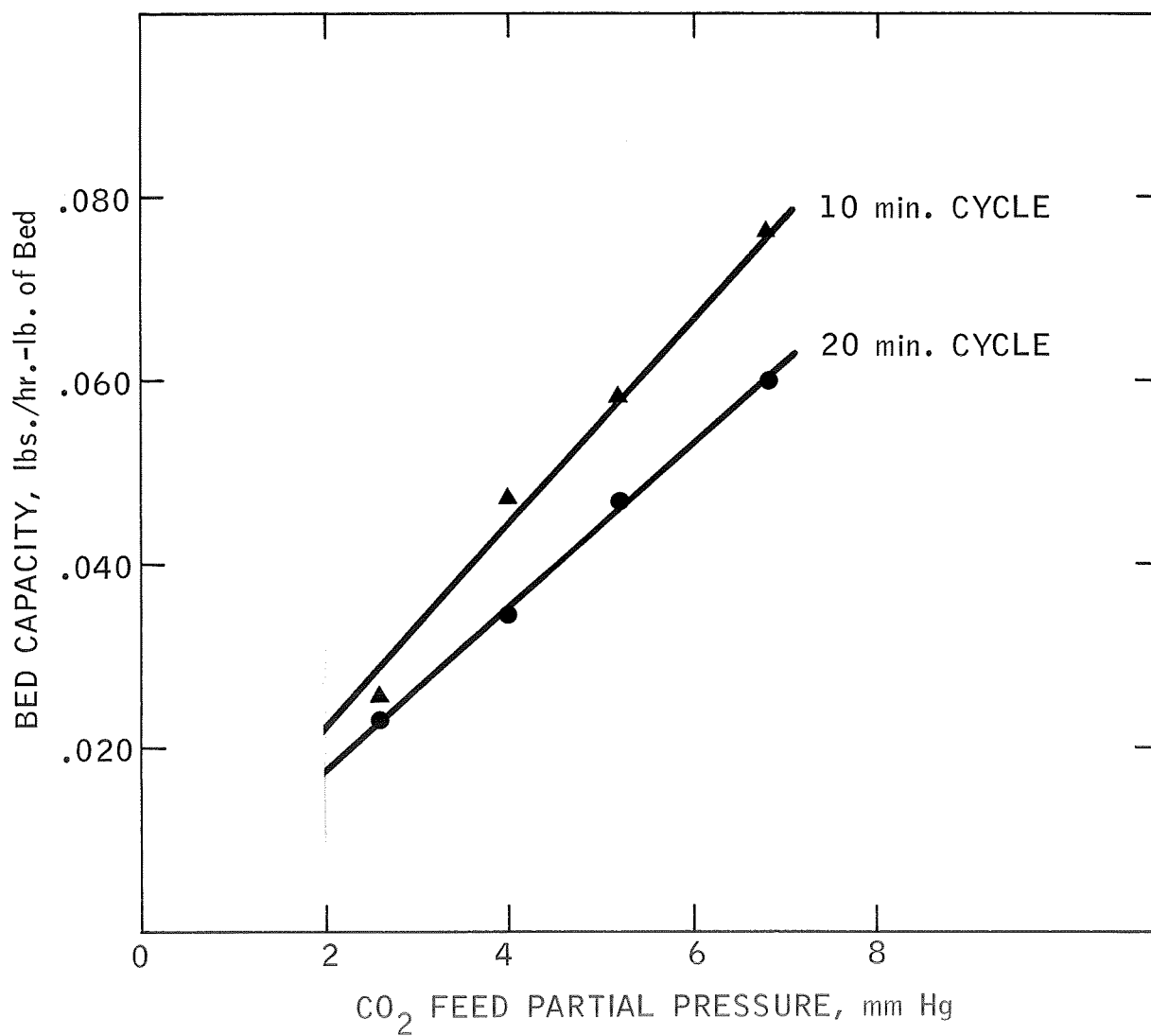
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4.10 Conclusions

A reduction of the bed desorption pressure from 2 to 0.7 torr by the use of a larger vacuum pump resulted in a 20% increase in CO_2 removal capacity. A further reduction in vacuum would be expected to result in still further improvement in system capacity. However, the ultimate advantage in improving system capacity by reducing the desorption bed pressure to very low levels (< .01 torr) would be less than 10% if equilibrium CO_2 desorption is controlling. The actual bed desorption pressure obtained in a space application would be limited by the desorption line pressure drop, i.e., on the hardware design, bed configuration, etc.

No improvement in purge desorption capacity was observed through the use of a sorbent filled PED cylinder. Air loss rates appear to be slightly higher using this PED mode configuration. The probable explanation for the failure of this concept to improve CO_2 capacity is an insufficient PED desorption vacuum pressure resulting from the combined effects of PED sorbent outgassing and pressure drop through the desorption bed.

Increasing the PED cylinder volume affects a modest increase in CO_2 removal capacity and slightly reduces air loss. A volume increase of 3 results in a 15 to 25% increase in capacity.

The use of a heated purge did not improve CO_2 system performance. Delaying the purge for 25% of the 1/2 cycle time can result in as much as a 35% reduction in air loss rate for comparable system capacities.

The CO_2 capacity of 13X Molecular Sieve is slightly poorer than 5A Sieve with purge assisted desorption.

CO_2 capacity increases in a near linear manner with an increase in CO_2 feed partial pressure over a range of pressure of 2.6 to 6.8 mm Hg pCO_2.

5. APPLICATION OF HEATLESS DESORPTION FOR SPACECRAFT ENVIRONMENTAL CONTROL

5.1 Space Shuttle Environmental Control

The Apollo carbon dioxide removal system, utilizing the irreversible reaction of CO_2 and LiOH, may not be practical for some space shuttle missions, because this system requires a quantity of LiOH sorbent in direct proportion to the mission duration and size of the crew. This may result in a favorable trade-off for a regenerable sorbent system for some missions. Also, space shuttle cabin humidity control using exclusively cooling and condensing heat exchangers and condensate traps may require radiator surfaces that are excessive for a re-entry type vehicle. Alternate approaches, obviating some of these problems may be appropriate for the environmental control of a space shuttle. Heatless and purge desorption methods offer such an approach.

5.1.1 Carbon Dioxide Control

Contract NAS 1-6918 and the current research have developed data appropriate for preliminary design of regenerative CO_2 removal systems. Estimates have been made for a typical four-man space shuttle mission using data obtained in these tests employing conventional purge assisted and PED modes of vacuum desorption. The results are presented in Table 15.

Table 15

CO_2 Removal System Requirements With Purge (PED) Desorption

Type of Desorption	Half-Cycle Time Mins.	Bed Capacity Lbs CO_2 / Lb Sorber-Hr	Air Loss Rate Lbs Air / Lb CO_2	5A Molecular Sieve Lbs. Bed	Air Flow SCFM
Vacuum	45	0.020	0.13	18.7	27
	17	0.025	0.44	15.0	22
PED**	40	0.025	0.13	15.0	22
	10	0.050	0.44	7.5	11

* Assumes four-man crew, cabin pressure 10 psia, CO_2 partial pressure 4 mm Hg, cabin temperature 75°F, CO_2 generation rate of 2.25 lbs/man-day.

** PED cylinder volume requirements are 0.93 and 0.47 ft^3 for the 40 and 10 min cycles, respectively.

The calculated bed size, air flow and cycle time require-
ments for two specified levels of air loss $0.13 \frac{lb\ air}{lb\ CO_2} \left(\frac{0.29\ lbs\ air}{day\text{-}man} \right)$

and $\frac{0.44\ lb\ air}{lb\ of\ CO_2} \left(\frac{1.0\ lb.\ air}{day\text{-}man} \right)$ are presented in Table 15. PED
desorption is seen to give higher capacity than vacuum desorption,
particularly at the higher air loss level. At a PED purge desorption
air loss of $1.0 \frac{lb\ of\ air}{day\text{-}man}$, which corresponds to an air loss rate of
$\frac{.44\ lb\ air}{lb\ CO_2}$, only 7.5 lbs of 5A Molecular Sieve/bed and 11 SCFM of dry
feed air are required to remove the CO_2 exhaled by four men. These
system size estimates are based on a CO_2 feed partial pressure of
4 mm Hg. Operation at higher cabin CO_2 levels would reduce the sorbent
weight and air flow requirements further. If higher air loss rates
could be tolerated, it would be possible to decrease the system cycle
time and substantially further reduce bed size and air flow require-
ments. This would amount to a trade-off in bed weight vs. the weight
in additional stored O_2 and N_2. Actual system requirements would
depend on the constraints of a particular space shuttle mission and
on the integration design of the CO_2 and humidity-temperature control
systems.

A regenerative CO_2 removal system, utilizing 5A Molecular Sieve
as the sorbent, must have a predrier since 5A Molecular Sieve strongly
adsorbes water, thereby reducing the capacity for CO_2. Thus, the efficiency
of the drier, as well as the manner in which it is coupled to the CO_2 re-
moval system will be very important in determining the performance and life
characteristics of the CO_2 removal system. The integration of regenerative
H_2O and CO_2 removal systems is discussed in the following paragraphs.

5.1.2 Humidity - Temperature Control By Heatless Air Conditioning

In a space shuttle, electrical power may be supplied by fuel
cells with water a product of the cell reaction. The availability of
this water makes respired and perspired water vapor expendable. This
atmospheric water vapor can be removed by condensation and subsequently
vented to space in a sublimator. However, this method would require a
large amount of heat transfer equipment for some missions, and radiator
space on a vehicle specifically designed for maneuverable re-entry and
thus radiator space would be at a premium.

PED purge desorption provides a convenient condenser and
evaporator which can be used to remove H_2O from spacecraft air
and concentrate it in a purge stream venting to space. For instance,
a silica gel desiccant bed would be alternately cycled between cabin
pressure and space vacuum. Desorption at space vacuum would require an
extremely small purge stream to effectively strip the H_2O from the
desiccant. Small molar purge flows must be used to minimize air loss.

Additional H$_2$O would be evaporated into the spacecraft atmosphere to maintain the desired concentration. To the extent that this humidification is carried out adiabatically, it would reduce the temperature of the treated air. Thus the net result of such a process would be the removal of both latent and sensible heat and the control of atmospheric humidity, i.e., heatless air conditioning of the spacecraft.

Process flowsheets illustrating the operation of these type systems are shown in Figure 16.

Clearly, the realization of effective desorption with tolerable air loss is mandatory to establish the practical feasibility of utilizing a heatless air conditioning system in a space shuttle. This can be appreciated when it is realized that the removal of 2.0 lbs/hr of H$_2$O from the spacecraft (the equivalent of the total average hourly heat produced by four astronauts) would result in the loss of nearly 0.5 lbs of air/day if the air loss rate was only .01 lbs of air/lb of H$_2$O. Such air loss rates have only been realized in the CO$_2$ experiments using very long cycle times and in PED operation. However, by far the bulk of the air lost in the CO$_2$ removal experiments arises from the surface of the 5A Molecular Sieve which appreciably co-adsorb the air during CO$_2$ adsorption. Such marked air desorption is not to be expected from silica gel.

Preliminary process flow calculations have been made for a four-man crew with a cabin pressure of 10 psia and an air dew point of 55°F. Air flow, water removal and water make up requirements for the removal of 500 and 800 BTU/hr-man respectively are presented in Table 16.

The equivalent H$_2$O generation represents the total 4-man crew perspiration rate at the given cabin temperature. Make-up water is that amount required if both sensible and latent heat loads are removed by means of the Heatless Air Conditioner system, i.e. the additional water that would have to be supplied by the adiabatic humidifier to account for the sensible heat load.

The silica-gel bed sorbent requirements were estimated using the design equation developed on Contract NAS 1-6918. The bed sizes were found to be quite reasonable. This sizing was based on a design that would dry the air to a dew point of -60°F. This level has been found to result in a reasonable 5A Molecular Sieve poisoning rate for a 45 day application. (ref. (1)).

Both gas flow and estimated bed weight requirements appear to be reasonable for a four-man shuttle cabin having 500 ft^3. Though a sizable portion of the dried air would have to be cooled and humidified in the adiabatic humidifier, enough dry air could still be made available to meet the air feed requirements of a rapid cycling CO$_2$ removal unit, operating with the PED heatless air conditioning system. However, it may be more desirable to have two independent drying units: one solely for air conditioning and one to pre-dry the air entering a molecular sieve CO$_2$ removal system. These questions will be discussed more fully in the section dealing with system integration.

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Figure 16

HEATLESS AIR CONDITIONING SYSTEMS

SYSTEM I   REMOVES WATER AND LATENT HEAT
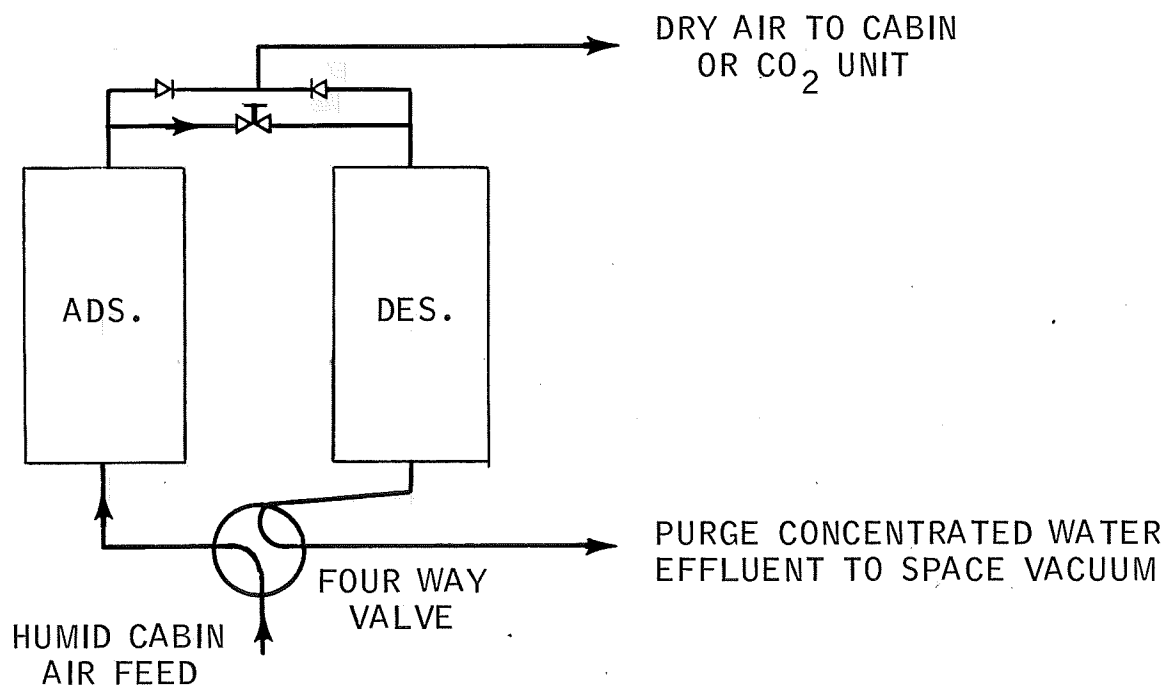
SYSTEM II   REMOVES WATER, LATENT AND SENSIBLE HEAT
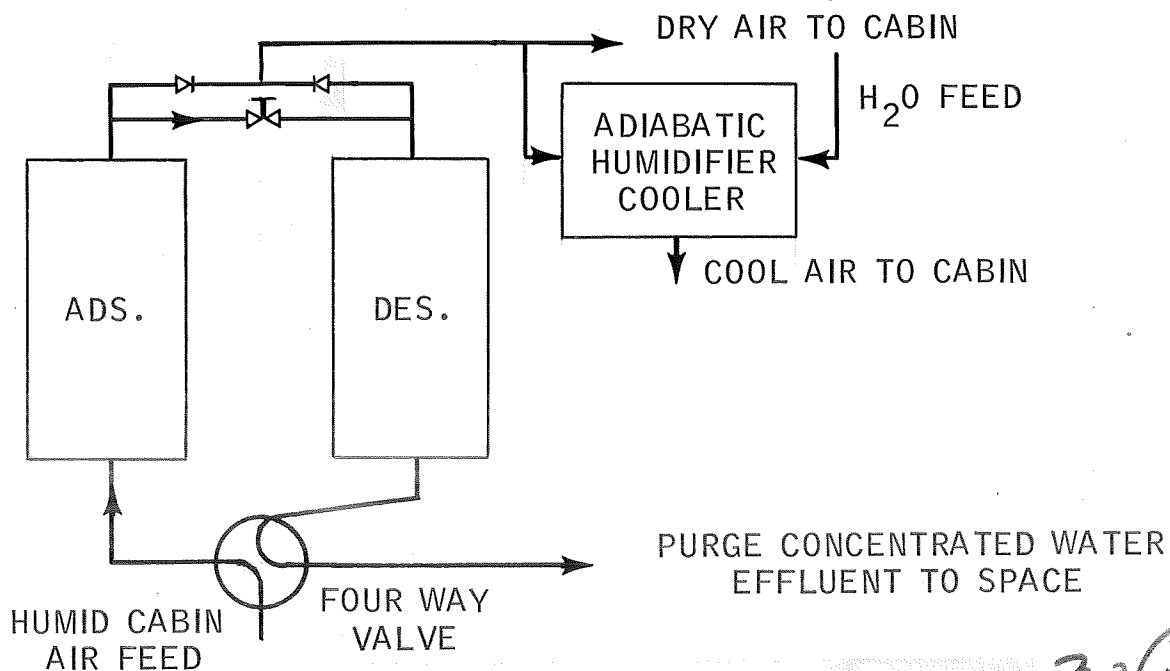
Table T6

Heatless Air Conditioning Process for a 4-Man Mission [1]

Cabin Temp. °F	Heat Load BTU/Hr-Man	Equivalent 4-Man H_2O Generation lbs/Hr	Make-up H_2O Required For Crew lbs/HR	Estimated Sorbent Requirements lbs/Bed	Required Gas Feed Rate SCFM	Humidifier Required Gas Feed Rate for H_2O Make-up SCFM	Minimum Gas Temperature Leaving Humidifier (WBT)°F
65°F	380 Latent / 420 Sensible	1.52					
	800	3.20	1.68	12.8	47	45	40
80°F	590 Latent / 210 Sensible	2.36					
	800	3.20	0.84	12.8	47	15	50
65°F	80 Latent / 420 Sensible	0.32					
	500	2.00	1.68	8.0	29[2]	45	40
70°F	150 Latent / 350 Sensible	0.60					
	500	2.00	1.40	8.0	29[2]	31	45
80°F	290 Latent / 210 Sensible	1.16					
	500	2.00	0.84	8.0	29	15	50

(1) Based on a cabin pressure of 10 psia and a cabin dew point of 55°F.

(2) Insufficient dry air from the HA unit is available to supply the humidifier requirement. A small amount of cabin air would have to be added, thus resulting in a somewhat higher temperature of the gas leaving the humidifier.

5.1.3 Combined Humidity - Temperature and Carbon Dioxide Control Systems Using Heatless Desorption

There are several ways in which Heatless Desorption drying and CO_2 removal can be coupled together. One has already been discussed in Section 2.2 and Figure 3 of this report. Other possible methods are given in Figures 17, 18, and 19. Each system has some inherent advantages and limitations.

In Figure 17, a four-bed system is described in which the desorbate from a CO_2 Heatless Desorption unit, using PED desorption, is also used to purge the desorption bed in the drying unit. This approach has the advantage of affecting very low air losses since one PED desorbate is used to purge both CO_2 and H_2O units. However, in this system the desorption pressure in the CO_2 unit will be higher than it would if it were vented directly to space vacuum. The added back pressure would result in a lower purge volume to assist CO_2 desorption which could reduce the capacity of the CO_2 unit.

The four bed parallel desorption process, depicted in Figure 18, uses individual, independent PED purge streams to desorb H_2O and CO_2, respectively. In this system, minimum desorption pressure is realized in both units as the purge is vented directly to space. This results in maximum purge gas volume for desorption and higher bed capacity. On the other hand, a much higher air loss could be realized in that two independent gas streams are required for purging. The same generalizations can be made about each process whether one, or both, use PED purge, or conventional purge assisted vacuum desorption. The same is also true whether or not the H_2O Heatless Desorption units are sized for air conditioning and pre-drying of the feed to the CO_2 unit, or just for pre-drying alone. (A H_2O removal Heatless Desorption unit designed just for drying the air feed to the CO_2 removal molecular sieve beds would be much smaller and would not require an adiabatic humidifier.)

Both four bed systems do, however, have one common advantage over a two bed composite type design shown in Figure 19 - they permit individual optimization of bed sizes and cycle times for both H_2O and CO_2 control systems. This could result in lower bed weights and power consumption. On the other hand, the two bed system eliminates considerable hardware and results in a much more compact and simple integrated unit.

A two bed composite Heatless Desorption unit, that was designed for complete humidity-temperature conditioning, would incur a large air pressure drop through the molecular sieve section since the total air flow requirements for H_2O removal would far exceed CO_2 bed requirements. The actual mode of system integration would depend, on the constraints of a given space shuttle mission.

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Figure 17

COMBINED HEATLESS AIR CONDITIONING
AND CARBON DIOXIDE CONTROL SYSTEMS

4 BEDS - SERIES DESORPTION
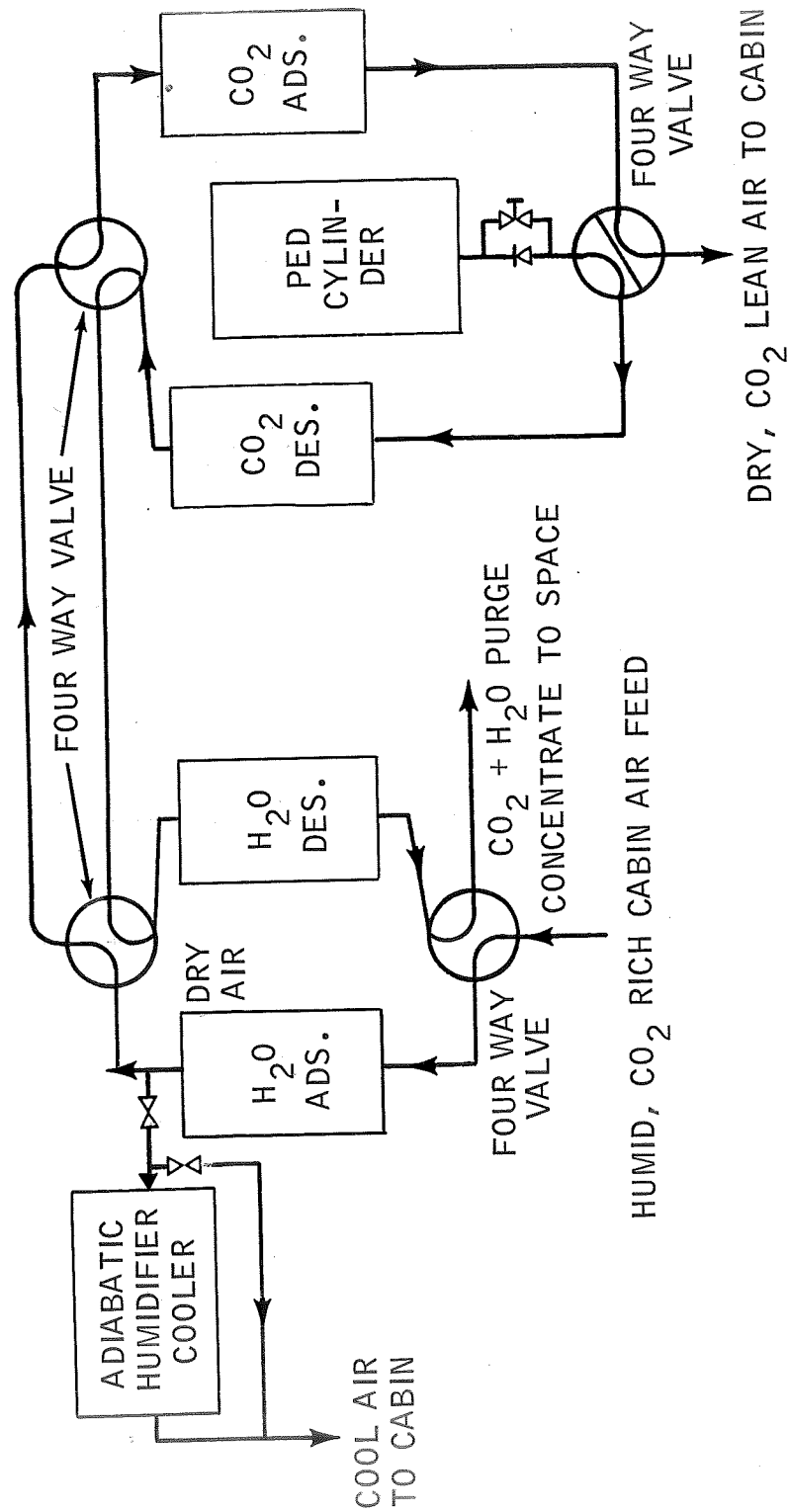
Figure 18

COMBINED HEATLESS AIR CONDITIONING
AND CARBON DIOXIDE CONTROL SYSTEMS

4 BEDS - PARALLEL DESORPTION
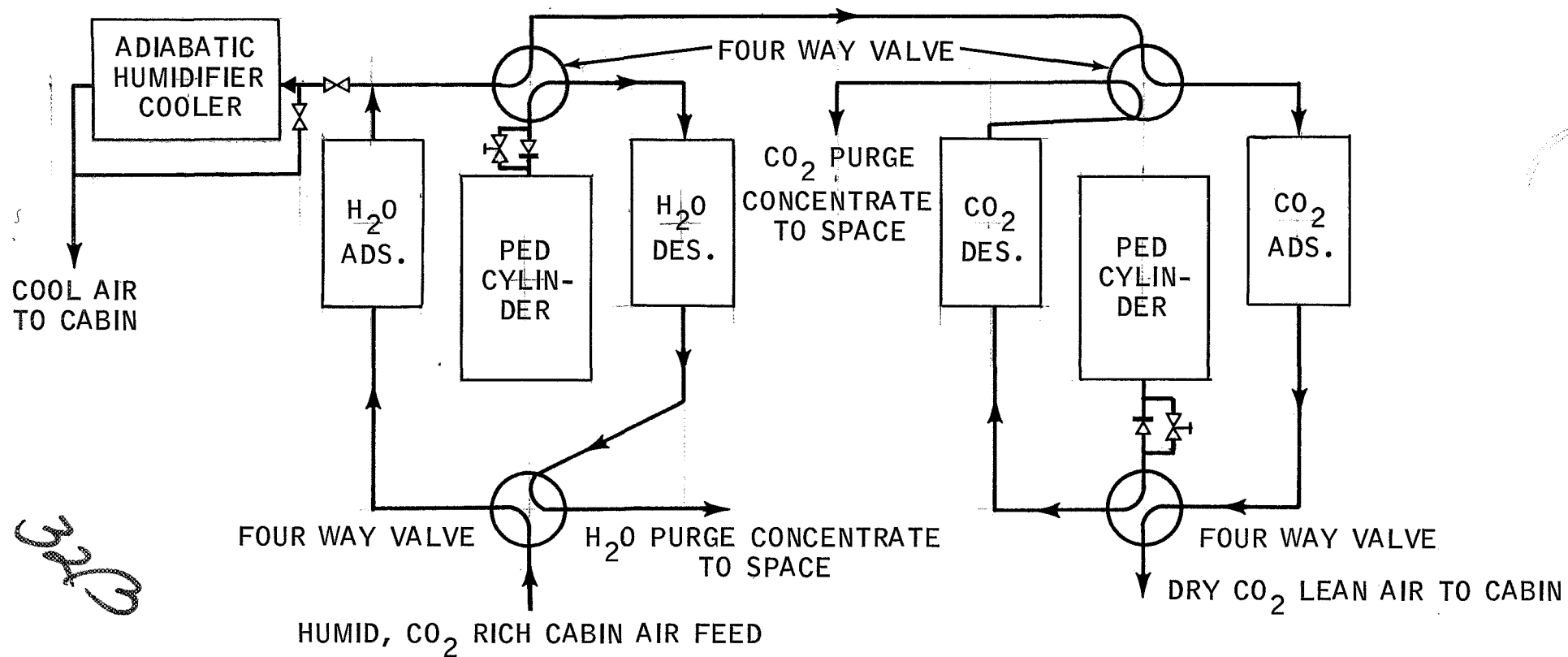
Figure 19

COMBINED HEATLESS AIR CONDITIONING
AND CARBON DIOXIDE CONTROL SYSTEMS

2 BEDS - COMPOSITE DESIGN
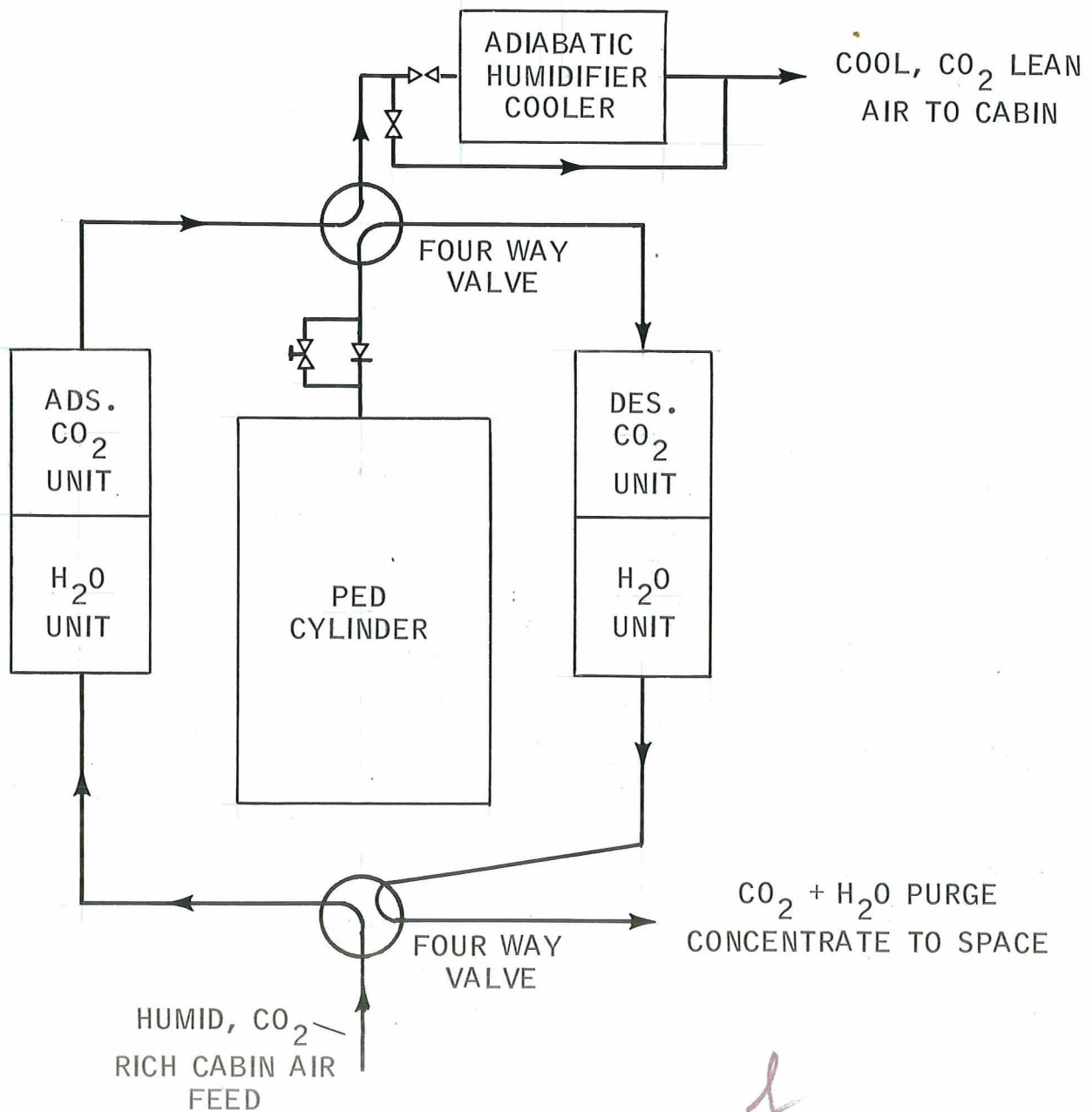
5.2 Auxiliary Drying System for Skylab Type System

Skylab is the United States' first experimental space station and is planned for launching in 1972. The AiResearch Manufacturing Co. in Los Angeles is presently developing the CO_2 removal system for Skylab. This system utilizes a composite bed of silica gel and molecular sieve to remove both water and CO_2 by vacuum desorption. In order to reduce CO_2 below the original design goal, process gas flow was increased, which then resulted in too much water being lost to space. A modification of the system would be required to save a portion of the water in the process air. One modification might be a condenser sublimator placed downstream of the CO_2 removal system. An alternate method would utilize a Heatless Desorption drying unit as depicted in Figure 20.

In this mode of operation, spacecraft air could be first dried in a Heatless Desorption system and then sent to the Skylab system. The CO_2-free air would be rehumidified during the desorption of the Heatless Desorption system. Operating in this manner, the Heatless Desorption drying unit would return H_2O to the spacecraft cabin air to maintain cabin humidity and H_2O loss at an acceptable level. Also, it would afford added protection to the Molecular Sieve CO_2 removal system by pre-drying the process air.

Estimates have been made of the additional sorbent weight and power required for this Heatless Desorption drying system. The results are summarized in Table 17.

Table 17

Sorbent and Power Requirements for Auxiliary
Heatless Desorption System Applicable to Skylab

Purge/ Feed	Sorbent Requirements lbs	Air Temperature Rise °F		Actual* Power Required Watts	Processed Air Dew Point °F
		Compressor	Bed		
1.10	4	16	<7	60	<10
1.05	6	8	<5	45	<0
1.03	15	4	<2	20	<10

Assuming Process air flow at 15 lbs/hr at dry bulb temp.
of 72°F and a dew point of 42°F; cabin pressure of 5 psi;
and air to be dried to a minimum of a 10°F dew point.

*Assuming 2x theoretical adiabatic compression power.

The above is an example of Heatless Desorption as it might be applied to Skylab. The mission constraints applied here are very general and are used only to develop the specific application example.

Figure 20

APPLICATION OF HEATLESS DESORPTION SYSTEM TO SKYLAB ENVIRONMENTAL CONTROL

(H_2O, CO_2) INLET

OUTLET (H_2O)

H_2O
ADSORBED

H_2O
DESORBED

MOSTLY CO_2
ADSORBED

CO_2
DESORBED

VAC.
$(CO_2$
VERY LITTLE
$H_2O)$

ADD-ON WATER SAVE SYSTEM

COMPOSITE H_2O, CO_2
BED AS PRESENTLY
DESIGNED, BUT
USED WITH A H_2O
SAVE SYSTEM
ADDED ON
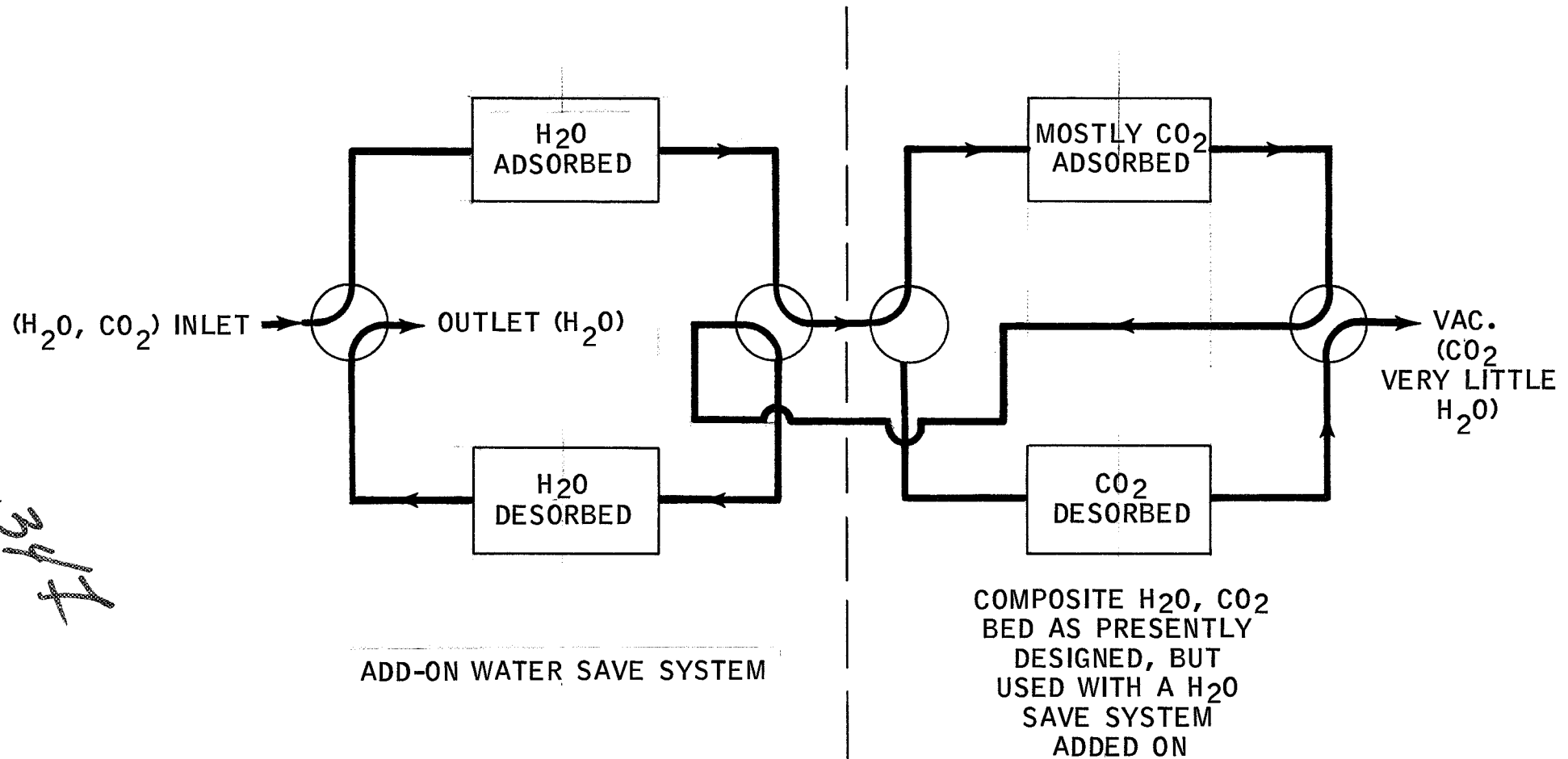
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* Note: Heatless Fractionation is another name used for Heatless Adsorption.

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7.   Appendix

Appendix 7.1

Purge to Feed Requirements in Heatless Desorption

In the Heatless Desorption process the use of a volumetric purge to feed ratio of at least 1:1 is necessary to insure that the desorption rate (average) is equal to the adsorption rate (average) without adding heat. Consider the situation shown in the diagram below (Figure A1-1).

Figure A1-1

Product

Purge

Throttle Valve

π_f

Unused Bed

π_p

Mass Transfer Zone

Saturation Zone

N_f
P_f
V_f

N_p
P_p
V_p

Feed
Adsorption

Purge Effluent
Desorption
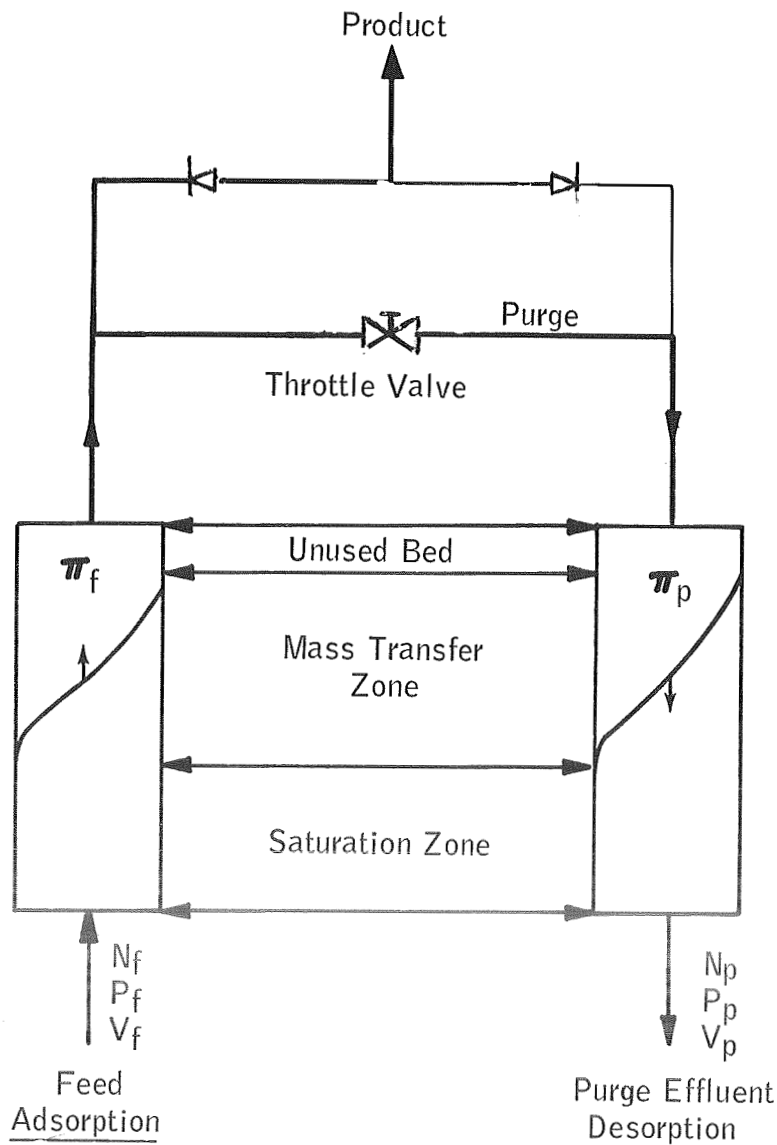
List of Symbols

P_p, P_f =   partial pressure in purge effluent and feed respectively

π_p, π_f =   total desorption and total adsorption pressure respectively

V_p, V_f =   actual volumes of purge and feed respectively

N_p, N_f =   moles of purge and moles of feed respectively

R =   gas constant

T =   absolute gas temperatures

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During adsorption, the front end of the bed equilibrates with the adsorbate at its partial pressure, P_f. The product gas of the adsorbing bed leaves much less concentrated in the adsorbable component. A portion of the adsorbate on this succeeding desorption cycle will be transferred from the bed to the gas stream. The partial pressure of the adsorbate in the purge effluent, P_p, will tend to re-equilibrate with the back end of the bed (front end of bed on adsorption). It would require a very large saturation zone to insure equilibration with the same volume flow of purge gas on desorption as was processed on adsorption. However, it can be assumed that some finite length of bed exists so that:

$$P_p \approx P_f$$

Providing breakthrough does not occur, and assuming the behavior of the gaseous components can be represented by the ideal gas law, an expression can be written which gives the total amount of adsorbate removed per unit cycle:

$$\frac{\text{Moles Adsorbed}}{\text{Cycle}} = \frac{P_f V_f}{RT}$$

Similarly, the amount of adsorbate desorbed by the purge is given by:

$$\frac{\text{Moles Desorbed}}{\text{Cycle}} = \frac{P_p V_p}{RT}$$

At steady state, the moles adsorbed per cycle must equal the moles desorbed per cycle or:

$$\frac{P_p V_p}{RT} = \frac{P_f V_f}{RT}$$

Therefore, if adsorption and desorption temperatures are the same, $V_p = V_f$ and the required purge to feed ratio, defined as $V_p : V_f$, will equal 1:1.

The use of a 1:1 purge to feed ratio is, however, a limiting case since temperature in the adsorbing and desorbing bed are not quite equal. If a purge to feed ratio greater than 1:1 is used (i.e., $V_p > V_f$) than P_p can be less than P_f and still have $\frac{P_p V_p}{RT} = \frac{P_f V_f}{RT}$. This means that at purge to feed ratios greater than 1:1 resaturation of the purge is not required in order to achieve equilibrium between adsorption and desorption. Thus, a smaller saturation zone can be tolerated and practical bed sizes can be used.

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Appendix 7.2

Reasons For Reporting Moisture Content
of Dried Gas In PPM

The amount of moisture remaining in the "dry" effluent from the desiccant beds can be expressed in several different ways. Throughout most of this report, moisture content has beed expressed in terms of PPM (Parts Per Million). This is defined by equation (1):

$$\text{PPM } H_2O \text{ in gas} = (P_{H_2O} \, P_{atm}) \times 10^6 \qquad (1)$$

$$P_{H_2O} = \text{ partial pressure } H_2O \text{ in gas}$$

$$P_{atm} = \text{ atmospheric pressure}$$

To compute the partial pressure of water remaining in the effluent from the drying beds, one then simply multiplies:

$$\text{PPM} \times P_{atm} \times 10^6 = P_{H_2O} \qquad (2)$$

It is this partial pressure that determines the amount of moisture carried into the molecular sieve beds, since:

Moles H_2O/Hr (into molecular sieve beds)

$$= kP_{H_2O}Vp \qquad (3)$$

$$k = \text{ proportionality constant } (\tfrac{1}{RT} \text{ for ideal gas})$$

$$V_p = \text{ actual volumetric flow rate (e.g., CFH) as operating pressure P}$$

$$P = \text{ actual operating system pressure}$$

By rearrangement:

Moles H_2O/Hr (into molecular sieve bed)

$$= k \, (PPM) \, (P_{atm}) \, (10^6) \, (V_p) \qquad (4)$$

$$= k' \, (PPM) \, (V_p) \qquad (5)$$

where $k' = k \, (P_{atm}) \, (10^6)$

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Equation (5) shows that the amount of moisture passing into the zeolite beds depends only on the PPM of H_2O in the gas and the actual gas flow rate at operating pressure. It does not depend on the actual operating pressure. Therefore, the fact that the experiments reported here were all conducted at a total pressure of about 11 psia is not important and the results obtained can be translated directly to other systems operating at different total pressures provided that:

(1) Actual gas flow rates through the system in cubic feet per pound of bed are maintained constant.

(2) Inlet dew points are the same (i.e., H_2O partial pressures are equal)

(3) Bed length, purge to feed ratios and adsorbent are the same.

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Appendix 7.3

Sample Calculation For CO_2 Sorption Experiments

Data

Feed rate to adsorbing bed: 30.5 SCFH
Bed weight: 0.4 lbs.
Half cycle time: 20 min.
Desorbate wet test meter reading: 0.1838 CF at 71°F in 20 min.

Figure A4-1

CO_2 CONCENTRATION IN FEED AND EFFLUENT FROM ADSORBING BED
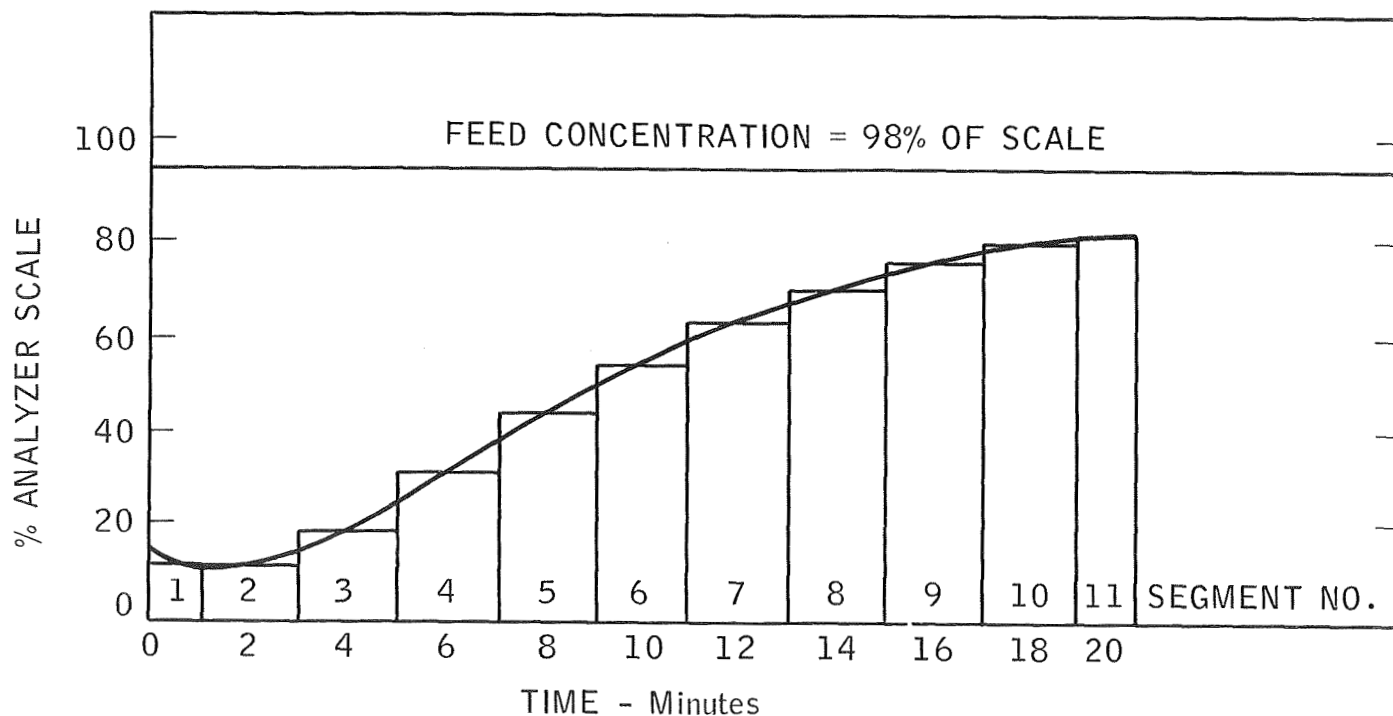
(1) The fraction of CO_2 adsorbed from the feed is calculated by graphical integration. The values of CO_2 partial pressure (psi) in Table A6-1 were obtained by converting CO_2 analyzer scale readings with a calibration curve provided by the manufacturer.

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Table A4-1

Segment	Median (% of Scale)	Psi	Seg. Width	Psi x Seg. Width
1	9.5	.015	1.1	.0165
2	11.5	.018	2.0	.036
3	17	.027	"	.054
4	29.5	.029	"	.098
5	42.25	.0745	"	.149
6	52.5	.095	"	.190
7	60.5	.113	"	.226
8	67	.127	"	.254
9	72	.138	"	.276
10	76.25	.1475	"	.295
11	78.75	.1535	1.2	.184
Totals			20.3	1.7785

Average product CO_2 concentration in psia is given by

$$\frac{\sum \text{psi x seg. width}}{\sum \text{seg. width}} = \frac{1.7785}{20.3} = .0876 \text{ psia}$$

Vol.Fraction CO_2 removed $= \dfrac{\text{Feed conc. - Prod. conc.}}{\text{Feed conc}} =$

$$\frac{.198 - .0986}{.198} = \boxed{.5576}$$

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(2) $\underline{\text{Volume of Desorbate}} = .1838 \dfrac{ft^3}{cycle} \times \dfrac{460 + 32}{460 + 71} \dfrac{SCF}{ft^3} \times 3 \dfrac{Cycles}{hr}$

$$= \boxed{.510 \ SCFH}$$

(3) Vol. CO_2 in Desorbate (hourly rate)

= Vol. Feed Rate (SCFH) x Vol. Fraction CO_2 in Feed x Vol Fraction CO_2 Removed

$= 30.5 \ SCFH \times \dfrac{.198}{14.7} \dfrac{PCO_2}{Patm} \times .5576 = \boxed{.2291 \ SCFH}$

(4) Vol. Fraction CO_2 in Desorbate

$= \dfrac{\text{Vol. } CO_2 \text{ in Desorbate}}{\text{Total Desorbate Vol}} = \dfrac{.2291 \ SCFH}{.5576 \ SCFH} = \boxed{.4492}$

Vol. Fraction Air in Desorbate

= 1.0 - Vol. Fraction CO_2 in Desorbate

= 1.0 - .4492 = .5508

(5) $\dfrac{\text{SCF Air Lost}}{\text{SCF } CO_2 \text{ Removed}} = \dfrac{.5598}{.4492} = \boxed{1.23 \longrightarrow \dfrac{\text{lb. Moles Air}}{\text{lb. Mole } CO_2}}$

(6) $\dfrac{\text{Lbs Air Lost}}{\text{Lb } CO_2 \text{ Removed}} = 1.23 \times \dfrac{28.97 \ Lbs, Air/Lb \ Mole}{44.0 \ \ Lbs, CO_2/Lb \ Mole}$

$$= \boxed{.81 \ \dfrac{\text{Lbs Air Lost}}{\text{Lb } CO_2 \text{ Removed}}}$$

(7) CO_2 Capacity (Lb CO_2/Hr/Lb Bed)

$= .2291 \ \dfrac{SCF \ CO_2 \ Removed}{Hr} \times \dfrac{1}{359} \dfrac{Lb \ Moles}{SCF} \times 44 \dfrac{Lbs \ CO_2}{Lb \ Mole} \times \dfrac{1}{.4 \ Lb \ Bed}$

$$= \boxed{.0720 \ \dfrac{Lbs \ CO_2/Hr}{Lb \ Bed}}$$

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Appendix 7.4

SPACE SHUTTLE DESIGN CRITERIA

- Crew   2-4 men for 7-30 days
         8-50 men for 2-7 days
         (2.25 lbs. CO_2/man-day)

- Total cabin pressure 7-10 psi but we should also consider 5-14.7 psia.

- Oxygen partial pressure - 3.1 psia for all total pressures.

- Allowable CO_2 concentration in cabin 5 mm with peaks to 8 mm.

- Cabin air leakage 3.5 lbs/day.

- Cabin volume 500 ft^3 (for 2-4 men)

- Heat loads - Average

                at 70°F   150 BTU/hr-man Latent
                           350 BTU/hr-man Sensible
                           500 BTU/hr-man Total

                at 65°F   80 BTU/hr-man Latent
                           420 BTU/hr-man Sensible
                           500 BTU/hr-man

                at 80°F   210 BTU/hr-man Sensible
                           290 BTU/hr-man Latent
                           500 BTU/hr-man Total

- Heat loads - Peak

                at 65°F   380 BTU/hr-man Latent
                           420 BTU/hr-man Sensible
                           800 BTU/hr-man Total

                at 80°F   590 BTU/hr-man Latent
                           210 BTU/hr-man Sensible
                           800 BTU/hr-man Total

- Fuel cell waste heat - 4000 BTU/hr
                at 125 - 150°F rejection temperature

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Appendix 7.5

Summary of Process Conditions for
Heatless Desorption CO_2 Runs

Run No.	Date	Column Sorbent	PED Cylinder Sorbent	Space Velocity	Cycle Times Mins.	Other Process Conditions, Comments etc.
A1-A6		Preliminary Testing of Systems, Leak Testing, etc.				
A-7	10-1-69	Linde 5A	None	145	5	
A-8	10-2-69	"	"	130	30	
A-9	10-2-69	"	"	130	20	
A-10	10-7-69	"	"	130	10	
A-11	10-9-69	"	"	130	5	
A-12	10-10-69	"	Linde 5A	130	30	
A-13	10-10-69	"	(380 gms)	130	20	
A-14	10-15-69	"	"	130	10	
A-15	10-16-69	"	"	130	5	
A-16	10-17-69	"	"	130	60	
A-17	10-20-69	"	"	130	60	CO_2 partial pressure 7.5 mm Hg
A-18	10-21-69	"	"	130	30	
A-19	10-22-69	"	"	130	20	
A-20	10-23-69	"	"	130	10	
A-21	10-24-69	"	"	130	5	
A-22	10-28-69	"	"	130	60	
A-23	10-29-69	"	"	130	60	
A-24	10-30-69	"	"	130	30	New Precision (vacuum pump leak)
A-25	10-31-69	"	"	130	20	
A-26	11-3-69	"	"	130	10	Scientific - High Vacuum Pump Installed
A-27	11-7-69	"	"	130	5	
A-28	11-10-69	"	"	130	20	
A-29	11-12-69	"	"	180	60	
A-30	11-13-69	"	"	180	30	
A-31	11-14-69	"	"	180	20	
A-32	11-17-69	"	"	180	10	
A-33	11-18-69	"	"	180	5	
A-34	11-24-69	"	"	60	60	
A-35	11-25-69	"	"	60	30	
A-36	11-26-69	"	"	60	20	
A-37	12-1-69	"	"	60	10	
A-38	12-3-69	"	"	60	5	
A-39	12-4-69	Davidson 13X	"	130	30	
A-40	12-5-69	"	"	130	20	
A-41	12-5-69	"	"	130	10	

Appendix 7.5 (continued)

Summary of Process Conditions for Heatless Desorption CO$_2$ Runs

Run No.	Date	Column Sorbent	PED Cylinder Sorbent	Space Velocity	Cycle Times Mins.	Other Process Conditions, Comments etc.
A-42	12-9-69	Davidson 13X	None	130	5	
A-43	12-10-69	Linde 5A	"	130	30	
A-44	12-11-69	"	"	130	20	
A-45	12-12-69	"	"	130	10	
A-46	12-12-69	"	"	130	5	
A-47	12-16-69	"	"	130	45	
A-48	12-17-69	"	"	130	60	
A-49	12-19-69	"	"	60	30	
A-50	12-19-69	"	"	60	30	
A-51	12-22-69	"	"	60	20	
A-52	12-23-69	"	"	60	45	
A-53	12-24-69	"	"	60	10	
A-54	1-5-70	"	"	60	5	
A-55	1-6-70	"	"	60	5	
A-56	1-7-70	"	"	60	30	
A-57	1-7-70	"	Linde 5A	60	30	
A-58	1-9-70	"	(380 gm)	60	20	
A-59	1-15-70	"	"	60	20	PED Cylinder Heated
A-60	1-16-70	"	"	60	10	to 150°F
A-61	1-20-70	Davidson 13X	None	60	30	
A-62	1-21-70	"	"	60	20	
A-63	1-22-70	"	"	60	10	
A-64	1-23-70	"	"	60	60	
A-65	1-26-70	"	"	60	60	
A-66	1-27-70	"	"	130	30	
A-67	1-28-70	"	"	130	20	
A-68	1-29-70	"	"	130	10	
A-69	1-30-70	"	"	130	5	
A-70	2-3-70	"	Davidson 13X	130	10	
A-71	2-3-70	"	(320 gm)	130	20	
A-72	2-4-70	"	"	130	30	
A-73	2-5-70	"	"	130	5	
A-74	2-6-70	"	"	130	60	
A-75	2-17-70	"	"	60	20	PED Cylinder Heated
A-76	2-17-70	"	"	60	10	to 300°F
A-77	2-18-70	"	"	60	20	PED Cylinder Heated
A-78	2-19-70	"	"	60	10	to 400°F
A-79	2-27-70	"	None	60	20	
A-80	3-2-70	Linde 5A	"	60	20	
A-81	3-4-70	"	"	60	10	
A-82	2-9-70	"	"	60	20	.071 ft.^{3} PED Cylinder

Appendix 7.5 (continued)

Summary of Process Conditions for
Heatless Desorption CO_2 Runs

Run No.	Date	Column Sorbent	PED Cylinder Sorbent	Space Velocity	Cycle Times Mins.	Other Process Conditions, Comments etc.
A-83	3-10-70	Linde 5A	None	60	10	.071 ft.³ PED
A-84	3-11-70	"	"	60	5	Cylinder
A-85	2-12-70	"	"	60	5	↓
A-86	3-13-70	"	"	60	30	
A-87	3-16-70	"	"	130	10	.071 ft.³ PED
A-88	3-17-70	"	"	130	20	Cylinder
A-89	3-18-70	"	"	130	70	↓
A-90	3-19-70	"	"	130	5	
A-91	3-23-70	"	"	180	5	.071 ft.³ PED
A-92	3-24-70	"	"	180	10	Cylinder
A-93	3-25-70	"	"	180	20	↓
A-94	3-26-70	"	"	180	30	
A-95	4-2-70	Davidson 13X	"	130	5	.071 ft.³ PED
A-96	4-6-70	"	"	130	10	Cylinder
A-97	4-7-70	"	"	130	20	↓
A-98	4-9-70	"	"	130	30	
A-99	4-13-70	Linde 13X	"	130	30	.071 ft.³ PED
A-100	4-14-70	"	"	130	30	Cylinder
A-101	4-20-70	"	"	130	20	↓
A-102	4-21-70	"	"	130	10	
A-103	4-22-70	"	"	130	5	
A-104	4-27-70	"	"	130	5	↓
A-105	5-1-70	"	"	130	10	.142 ft.³ PED
A-106	5-4-70	"	"	130	20	Cylinder
A-107	5-5-70	"	"	130	30	↓
A-108	5-6-70	"	"	130	5	
A-109	5-7-70	"	"	60	30	.142 ft.³ PED
A-110	5-8-70	"	"	60	20	Cylinder
A-111	5-8-70	Linde 5A	"	130	30	.142 ft.³ PED
A-112	5-13-70	"	"	130	20	Cylinder
A-113	5-15-70	"	"	130	10	↓
A-114	5-18-70	"	"	130	5	
A-115	5-19-70	"	"	130	10	Feed CO_2 Partial Pressure 2.6 mm Hg
A-116	5-19 70	"	"	130	10	Feed CO_2 Partial Pressure 5.2 mm Hg
A-117	5-25-70	"	"	130	10	Feed CO_2 Partial Pressure 6.8 mm Hg
A-118	5-26-70	"	"	130	20	Feed CO_2 Partial Pressure 5.2 mm Hg
A-119	5-27-70	"	"	130	20	Feed CO_2 Partial Pressure 2.6 mm Hg
A-120	5-27-70	"	"	130	20	Feed CO_2 Partial Pressure 6.8 mm Hg

Appendix 7.5 (continued)

Summary of Process Conditions for
Heatless Desorption CO_2 Runs

Run No.	Date	Column Sorbent	PED Cylinder Sorbent	Space Velocity	Cycle Times Mins.	Other Process Conditions, Comments etc.
A-121	5-28-70	Linde 5A	None	130	10	.142 ft.^{3} PED Cylinder
A-122	6-1-70	"	"	130	10	.142 ft.^{3} PED 5 min delayed purge
A-123	6-2-70	"	"	130	10	.142 ft.^{3} PED Cylinder .5 min. delayed purge
A-124	6-2-70	"	"	130	5	.142 ft.^{3} PED cylinder .5 min delayed purge
A-125	6-3-70	"	"	130	5	.142 ft.^{3} PED Cylinder 1 min delayed purge
A-126	6-4-70	"	"	130	20	.142 ft.^{3} PED Cylinder 1 min delayed purge
A-127	6-4-70	"	"	130	20	.142 ft.^{3} PED Cylinder 2 min. delayed purge
A-128	6-5-70	"	"	130	20	.142 ft.^{3} PED Cylinder 5 min delayed purge
A-129	6-5-70	"	"	130	5	Adsorption pressure 25.9 mm Hg
A-130	6-8-70	"	"	130	10	Adsorption pressure 25.9 mm Hg
A-131	6-8-70	"	"	130	20	Adsorption pressure 25.9 mm Hg
A-132	6-9-70	"	"	130	30	Adsorption pressure 25.9 mm Hg
A-133	6-9-70	"	"	130	5	Adsorption pressure 17.9 mm Hg
A-134	6-10-70	"	"	130	10	Adsorption pressure 17.9 mm Hg
A-135	6-10-70	"	"	130	20	Adsorption pressure 17.9 mm Hg
A-136	6-11-70	"	"	130	30	
A-137	6-12-70	"	"	130	10	

APPENDIX 7.6

RESULTS OF HEATLESS DESORPTION
CARBON DIOXIDE EXPERIMENTS

Nomenclature

Symbol	Description	Units
F	Total Volumetric Feed Rate to System	SCFH
P	Partial Pressure of Carbon Dioxide in Feed at atmospheric pressure	psia
P_f'	Partial Pressure of Carbon Dixoide in Feed adsorption pressure	psia
P_e'	Partial Pressure of Carbon Dioxide in Product at adsorption pressure	psia
T	Temperature of Process Equipment	°F
V_f	Volume Fraction of Carbon Dioxide in Feed	dimensionless
V_r	Volume Fraction of Carbon Dioxide Removed from Feed	dimensionless
V_c	Volume of Carbon Dioxide In Desorbate	SCFH
V	Volume of Purge Desorbate	SCFH
V_d	Volume Fraction of Carbon Dioxide in Desorbate	dimensionless
V_{ad}	Volume Fraction of Air in Desorbate	dimensionless
α	Ratio of SCFH of air Lost to SCFH CO_2 Removed	dimensionless
B	Ratio of lbs. of Air Lost to lbs. of CO_2 Removed	dimensionless
C	System Carbon Dioxide Removal Capacity	$\dfrac{\text{lbs. of } CO_2}{\text{hour-lb. of bed}}$
S_v	Feed Space Velocity	$\dfrac{\text{CFH}}{\text{lb. of bed}}$

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

A–1 Through A–22 Were Preliminary Test Items

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A–23	A–1	35.7	.118	.085	.061	72	.0080	.2820	.081	.121	.670	.330	.489	.323	.0251	130
A–24	A–1		.113	.083	.056	72	.0077	.3250	.090	.117	.770	.230	.299	.197	.0280	
	A–2		.113	.083	.054	72	.0077	.3500	.096	.116	.830	.170	.205	.135	.0298*	
													.257*	.170*	.0290*	
A–25	A–1		.115	.084	.049	73	.0078	.4170	.116	.196	.590	.410	.694	.457	.0360	
	A–2		.115	.084	.051	73	.0078	.3930	.110	.162	.680	.320	.470	.310	.0341	
	B–1		.113	.085	.053	73	.0077	.3770	.103	.148	.700	.300	.429	.283	.0320	
	B–2		.113	.085	.054	73	.0077	.3650	.101	.156	.650	.350	.538	.355	.0313	
														.350*	.034*	
A–27	1	35.8	.118	.0864	.037	73	.008	.6863	.196	.403 / .033	.487	.512	1.051	.692	.0608	
	2		.118	.0864	.031	73	.008	.6354	.182	.365 / .033	.497	.503	1.008	.664	.0563	
														.678*	.0585*	
A–28	1		.120	.0875	.057	72	.0082	.3406	.100	.154	.645	.354	.548	.361	.0309	
	2		.120	.0875	.057	72	.0082	.3406	.100	.152 / .054	.654	.345	.527	.347	.0309	
	1		.116	.0845	.050	73	.0079	.4054	.114	.164 / .058	.695	.304	.437	.288	.0354	
	2		.116	.0846	.050	73	.0079	.4054	.114	.158 / .056	.721	.278	.386	.254	.0354	
														.313*	.0337*	
A–29	1	46.5	.112	.0824	.068	71	.0076	.1699	.060	.066	.905	.095	.105	.069	.0186	180
A–30	1		.104	.0762	.056	72	.0071	.2598	.085	.118 / .063	.726	.273	.376	.248	.0265	
	2		.104	.0762	.056	72	.0071	.2598	.085	.119 / .063	.716	.283	.396	.261	.0265	
														.254*	.0265*	
	1		.114	.0839	.061	74	.0078	.2718	.098	.121 / .065	.812	.187	.231	.152	.0305	
	2		.114	.0829	.061	73	.0078	.2718	.098	.120 / .064	.816	.183	.224	.147	.0305	
														.150*	.0305*	

* Denotes average values for run

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-31	1 AM	46.5	.108	.0802	.0557	72	.0073	.3055	.1037	.1673	.6134	.3802	.6134	.4042	.0321	180
	2 AM		.108	.0802	.0592	72	.0073	.3242	.1101	.1642	.6705	.3295	.4914	.3238	.0341	
	1 PM		.112	.0832	.0572	72	.0076	.3125	.1104	.1634	.6756	.3244	.4802	.3165	.0341	
	2 PM		.112	.0832	.0572	72	.0076	.3125	.1104	.1595	.6922	.3078	.4447	.2931	.0341	
													.334*	.034*		
A-32	1 AM	46.5	.113	.0831	.0456	71	.0077	.4513	.1616	.2722	.5937	.4063	.6844	.4510	.0450	180
	2 AM		.113	.0828	.0454	71	.0077	.4517	.1618	.2507	.6454	.3546	.5494	.3621	.050	
	1 PM		.112	.0798	.0427	73	.0076	.4649	.1643	.2510	.6546	.3454	.5277	.3478	.0508	
	2 PM		.112	.0798	.0442	73	.0076	.4649	.1643	.2382	.6898	.3102	.4497	.2964	.0508	
													.335*	.050*		
A-33	1 AM	46.5	.112	.0824	.0353	72	.0076	.5716	.2020	.4102	.4924	.5076	1.0308	.6793	.0625	180
	2 AM		.112	.0824	.0368	72	.0076	.5534	.1956	.3551	.5508	.4492	.8155	.5374	.0605	
	1 PM		.112	.0824	.0353	75	.0076	.5716	.2020	.3736	.5407	.4593	.8495	.5598	.0625	
	2 PM		.112	.0824	.0368	75	.0076	.5534	.1956	.3587	.5453	.4547	.8339	.5495	.0605	
													.582*	.0615*		
A-34	1 AM	16.0	.112	.0817	.0437	73	.0076	.4651	.0566	.0795	.7119	.2881	.4047	.2667	.0175	60
	2 AM		.112	.0817	.0459	73	.0076	.4382	.0528	.0755	.6993	.3007	.4300	.2834	.0163	
													.275*			
A-35	1 AM		.118	.0884	.0277	73	.0080	.6867	.0879	.1130	.7779	.2221	.2855	.1881	.0272	
	2 AM		.118	.0884	.0270	73	.0080	.6946	.0889	.1145	.7764	.2236	.288	.1898	.0275	
	1 PM		.112	.0839	.0277	72	.0076	.6698	.0814	.1179	.6904	.3096	.4484	.2955	.0252	
	2 PM		.112	.0839	.0277	73	.0076	.6692	.0814	.1151	.7072	.2928	.4140	.2728	.0252	
													.230*	.0263*		
A-36	1 AM		.104	.0762	.0182	73	.0071	.7598	.0863	.1500	.5753	.4247	.7382	.4865	.0267	60
	2 AM		.104	.0762	.0190	73	.0071	.7507	.0853	.1404	.6076	.3924	.6458	.4256	.0264	
	1 PM		.114	.0835	.0183	76	.0078	.7808	.0974	.1446	.6736	.3264	.4846	.3194	.0301	
	2 PM		.114	.0835	.0205	76	.0078	.7545	.0942	.1433	.6574	.3426	.5211	.3434	.0291	
													.400*	.0286*		

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-37	1 AM	16.1	.115	.0846	.0088	71	.0078	.8960	.1125	.2337	.4814	.5186	1.0073	.7099	.0348	60
	2 AM		.115	.0850	.0103	71	.0078	.8788	.1104	.2167	.5261	.4739	.9008	.5936	.0341	
	1 PM		.115	.0850	.0089	71	.0078	.8953	.1124	.2200	.5109	.4891	.9573	.6308	.0347	
	2 PM		.115	.0850	.0103	71	.0078	.8788	.1104	.2116	.5217	.4783	.9168	.6041	.0341	
														.6346*	.0344*	
A-38	1 AM	16.1	.110	.0802	.0044	70	.0075	.9451	.1141	.3742	.3049	.6951	2.2798	1.5023	.0353	
	2 AM		.110	.0806	.0059	70	.0075	.9268	.1119	.3363	.3327	.6673	2.0057	1.3218	.0346	
	1 PM		.112	.0820	.0029	71	.0076	.9646	.1180	.3625	.3255	.6745	2.0722	1.3656	.0365	
	2 PM		.112	.0820	.0044	71	.0076	.9463	.1158	.3276	.3535	.6465	1.8289	1.2052	.0358	
														1.3487*	.0356*	
A-39	1 AM	35.8	.121	.0924	.0567	70	.0082	.3864	.1134	.1228	.9335	.0765	.0838	.0546	.0350	60
	2 AM		.121	.0924	.0612	70	.0082	.3377	.0991	.1129	.8777	.1223	.1393	.0918	.0306	
	1 PM		.116	.0865	.0551	71	.0079	.3630	.1027	.1113	.9227	.0773	.0838	.0552	.0317	
	2 PM		.116	.0865	.0574	71	.0079	.3364	.0951	.1155	.8234	.1766	.2145	.1414	.0294	
														.0858*	.0317*	
A- 40	1 AM	35.7	.107	.078	.0660	71	.00729	.380	.0990	.146	.677	.323	.477	.314	.0306	130
	2 AM		.107	.078	.0680	71	.00727	.360	.0937	.154	.607	.393	.647	.427	.0290	
	1 PM		.115	.084	.0670	72	.00783	.400	.1130	.146	.675	.325	.482	.318	.0349	
	2 PM		.115	.085	.0680	72	.00783	.410	.1150	.148	.778	.222	.286	.189	.0355	
														.312*	.0325*	
A- 41	1 AM	35.7	.131	.101	.0570	73	.00892	.580	.186	.265	.702	.298	.424	.280	.0575	130
	2 AM		.131	.101	.0590	73	.00892	.560	.180	.256	.704	.296	.421	.277	.0557	
	1 PM		.114	.086	.0440	72	.00776	.500	.139	.221	.631	.369	.586	.386	.0430	
	2 PM		.114	.086	.0540	72	.00776	.500	.139	.229	.606	.394	.650	.428	.0430	
														.344*	.0498*	
A-42	1 AM	35.7	.120	.084	.0320	72	.00816	.710	.208	.380	.547	.453	.829	.546	.0643	130
	2 AM		.120	.089	.0380	72	.00816	.670	.196	.373	.526	.474	.902	.596	.0606	
	1 PM		.114	.086	.0340	72	.00760	.700	.195	.384	.507	.493	.981	.647	.0605	
	2 PM		.114	.086	.0370	72	.00776	.670	.186	.368	.506	.494	.978	.645	.0575	
														.608*	.0607*	
A-43	1 AM	35.7	.107	.080	.069	73	.00729	.350	.0910	.114	.798	.202	.253	.167	.0282	130
	2 AM		.107	.079	.067	73	.00729	.370	.0966	.118	.817	.183	.224	.148	.0297	
	1 PM		.108	.081	.069	73	.00735	.360	.0948	.113	.837	.163	.195	.128	.0293	
	2 PM		.108	.080	.069	73	.00735	.360	.0948	.113	.837	.163	.195	.128	.0293	
														.144*	.0291*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-44	1 AM	35.7	.112	.085	.068	72	.00762	.390	.107	.151	.707	.293	.414	.273	.0332	130
	2 AM		.112	.085	.067	72	.00762	.400	.109	.148	.737	.263	.357	.235	.0338	
	1 PM		.114	.083	.067	72	.00776	.410	.114	.151	.755	.245	.325	.215	.0353	
	2 PM		.114	.084	.065	72	.00776	.430	.120	.146	.822	.178	.217	.143	.0372	
														.218*	.0349*	
A-45	1 AM	35.7	.108	.079	.108	73	.00735	.520	.137	.234	.586	.414	.707	.466	.0424	130
	2 AM		.108	.079	.108	73	.00735	.520	.137	.216	.634	.366	.578	.380	.0424	
	1 PM		.110	.080	.110	73	.00749	.510	.137	.231	.592	.408	.689	.454	.0424	
	2 PM		.110	.080	.110	73	.00749	.510	.137	.219	.625	.375	.600	.396	.0424	
														.424*	.0424*	
A-46	1 AM	35.7	.109	.080	.109	71	.00742	.650	.173	.346	.500	.500	1.000	.659	.0535	130
	2 AM		.109	.081	.109	71	.00742	.630	.168	.335	.502	.498	.982	.647	.0520	
	1 PM		.115	.085	.115	72	.00782	.640	.179	.361	.496	.504	1.020	.672	.0554	
	2 PM		.115	.085	.115	72	.00782	.640	.179	.335	.534	.466	.872	.576	.0554	
														.637*	.0541*	
A-47	1 AM	35.8	.103	.075	.056	74	.00702	.250	.063	.098	.642	.358	.558	.368	.0195	130
	2 AM		.103	.075	.056	74	.00702	.230	.058	.092	.631	.369	.585	.386	.0179	
	1 PM		.115	.084	.060	75	.00782	.270	.075	.094	.803	.197	.245	.162	.0234	
	2 PM		.115	.084	.060	75	.0782	.270	.075	.094	.803	.196	.245	.162	.0234	
														.269*	.0210*	
A-48	1 PM		.107	.079	.060	74	.00729	.230	.060	.069	.872	.128	.147	.097	.0186	
	2 PM		.107	.079	.060	74	.00729	.230	.060	.068	.885	.115	.130	.086	.0186	
														.0914*	.0186*	
A-49	1 PM	16.2	.114	.087	.038	75	.00777	.570	.0717	.070	1.000	.01	.01	.00659	.0222	60
	2 PM		.114	.083	.039	75	.00777	.530	.0669	.067	1.000	.01	.01	.00659	.0207	
														.0065*	.0215*	
A-50	1 AM	16.2	.126	.092	.030	73	.00857	.670	.0930	.111	.837	.163	.195	.129	.0287	
	2 AM		.126	.092	.031	73	.00857	.660	.0917	.111	.827	.273	.330	.218	.0283	
	1 PM		.115	.084	.031	74	.00782	.630	.0799	.109	.732	.268	.366	.241	.0247	
	2 PM		.115	.083	.030	74	.00782	.640	.0813	.106	.767	.233	.304	.200	.0251	
														.197*	.0267*	

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-51	1 AM	16.8	.128	.0980	.0253	71	.0087	.7418	.1084	.1397	.7759	.2241	.2888	.1903	.0335	60
	2 AM		.128	.0980	.0268	71	.0087	.7265	.1062	.1402	.7575	.2425	.3201	.2109	.0328	
	1 PM		.117	.0896	.0260	72	.0080	.7098	.0954	.1352	.7056	.2944	.4172	.2749	.0295	
	2 PM		.117	.0896	.0253	72	.0080	.7176	.0964	.1354	.7120	.2880	.4045	.2666	.0298	
														.2357*	.0314 *	
A-52	1 PM	16.8	.126	.0965	.0414	74	.0086	.5710	.0824	.0924	.8918	.1082	.1213	.0799	.0255	
	2 PM		.126	.0965	.0398	74	.0086	.5876	.0849	.0963	.8816	.1184	.1343	.0885	.0262	
														.2357*	.0259*	
A-53	1 AM	16.8	.112	.0831	.0164	74	.0076	.8026	.1025	.2036	.5034	.4966	.9865	.6501	.0317	60
	2 AM		.112	.0831	.0171	74	.0076	.7942	.1014	.1982	.5116	.4884	.9547	.6291	.0313	
	1 PM		.108	.0802	.0156	74	.0073	.8055	.0988	.1992	.4960	.5040	1.0161	.6692	.0395	
	2 PM		.108	.0798	.0148	74	.0073	.8145	.0999	.1854	.5388	.4612	.8560	.5641	.0309	
														.6282*	.0316 *	
A-54	1 AM	16.8	.116	.0854	.0074	72	.0079	.9133	.1212	.2063	.2958	.6042	1.5265	1.0060	.0375	60
	2 AM		.116	.0857	.0074	72	.0079	.9137	.1213	.2772	.4376	.5624	1.2852	.8469	.0375	
	1 PM		.112	.0839	.0075	72	.0076	.9106	.1163	.2666	.4280	.5720	1.2477	.8222	.0366	
	2 PM		.112	.0829	.0076	72	.0076	.9106	.1163	.2717	.4280	.5720	1.3364	.8807	.0359	
														.8890*	.0369*	
A-55	1 AM	16.8	.112	.0839	.0097	72	.0076	.8844	.1129	.3138	.3598	.6404	1.7798	1.1729	.0348	60
	2 AM		.112	.0839	.0075	72	.0076	.9106	.1163	.2985	.3896	.6104	1.5667	1.0325	.0359	
	1 PM		.115	.0862	.0067	73	.0078	.9223	.1209	.3430	.3525	.6475	1.7369	1.2105	.0374	
	2 PM		.115	.0862	.0075	73	.0078	.9130	.1196	.3115	.3834	.6166	1.6082	1.0598	.0370	
														1.1189*	.0363*	
A-56	1 AM	16.8	.104	.0783	.0385	75	.0071	.5083	.0606	.1098	.5519	.4481	.8119	.5350	.0187	
	2 AM		.104	.0783	.0278	75	.0071	.6450	.0770	.1025	.7512	.2488	.3312	.2183	.0238	
	1 PM		.110	.0828	.0271	75	.0075	.6727	.0848	.1080	.7851	.2149	.2737	.1804	.0262	
	2 PM		.110	.0828	.0263	75	.0075	.6824	.0860	.1080	.7963	.2037	.2558	.1686	.0266	
														.2756*	.0238*	
A-57	1 AM	16.8	.117	.0857	.0190	73	.0080	.7782	.0954	.1179	.8092	.1908	.2358	.1554	.0295	
	2 PM		.117	.0826	.0236	73	.0080	.7143	.0876	.1128	.7766	.2234	.2877	.1896	.0271	
	1 PM		.115	.0838	.0226	73	.0078	.7328	.0898	.1152	.7795	.2205	.2829	.1864	.0277	
	2 PM		.115	.0838	.0226	73	.0078	.7303	.0895	.1134	.7892	.2108	.2671	.1760	.0277	
														.1769*	.0280*	

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-58	1 AM	16.8	.107	.0787	.0137	73	.0073	.8323	.1020	.1454	.7015	.2985	.4255	.2804	.0315	60
	2 AM		.107	.0787	.0147	73	.0073	.8132	.0997	.1404	.7101	.2899	.4083	.2691	.0308	
	1 PM		.107	.0787	.0125	73	.0073	.8412	.1031	.1461	.7057	.2943	.4170	.2748	.0319	
	2 PM		.107	.0787	.0132	73	.0073	.8323	.1020	.1420	.7183	.2817	.3922	.2585	.0315	
														.2707*	.0314*	
A-59	1 PM		.110	.0809	.0162	77	.0075	.7998	.1008	.1237	.8149	.1851	.2271	.1497	.0311	
	2 PM		.110	.0809	.0192	77	.0075	.7627	.0961	.1216	.7903	.2097	.2654	.1749	.0297	
														.1623*	.3040*	
A-60	1 AM	16.8	.109	.0808	.0087	77	.00747	0.892	0.1119	0.2523	.4435	.5565	1.254	.8269	.0346	60
	2 AM				.0094	77		0.884	0.1109	0.2473	.4484	.5516	1.230	.8104	.0343	
	1 PM				.0074	77		0.908	0.1140	0.1999	.5702	.4297	.5753	.4965	.0353	
	2 PM				.0079	77		0.902	0.1131	0.1951	.5797	.4203	.7250	.4778	.0349	
														.6530*	.03481*	
A-61	1 AM		.1118	.0819	.0379	78	.00761	0.537	0.0686	0.0915	.7497	.2503	.3339	.5066	.0212	
	2 AM		.1118	.0819	.0351	76	.00761	0.571	0.0729	0.0905	.8055	.1945	.2415	.3664	.0225	
	1 PM		.1180	.1180	.0375	76	.00800	0.566	0.0761	0.0982	.7644	.2356	.3082	.2031	.0235	
	2 PM		.1180	.1180	.0395	76	.00800	0.543	0.0730	0.0955	.7644	.2356	.3083	.2031	.0226	
														.3270*	.0225*	
A-62	1 AM		.1098	.0804	.0287	76	.00746	0.643	0.0806	0.1165	.6918	.2083	.4455	.2936	.0249	
	2 AM		.1089	.0804	.0287	76	.00746	0.643	0.0806	0.1143	.7052	.2948	.4180	.2755	.0249	
	1 PM		.1118	.0819	.0308	76	.00761	0.624	0.0798	0.1184	.6740	.3260	.4837	.3187	.0249	
	2 PM		.1118	.0819	.0307	76	.00761	0.625	0.0799	0.1157	.6906	.3094	.4880	.2950	.0247	
														.2960*	.0248*	
A-63	1 AM		.1118	.0815	.0216	76	.00761	0.735	.0939	0.1780	.5275	.4725	.8857	.5903	.0290	
	2 AM				.0218	76		0.733	.0937	0.1729	.5419	.4581	.8453	.5571	.0290	
	1 PM				.0291	76		0.766	.0979	0.1713	.5715	.4285	.7497	.4941	.0303	
	2 PM				.0200	76		0.755	.0965	0.1663	.5803	.4197	.7232	.4766	.0798	
														.5300*	.0295*	
A-65	1 PM		.1138	.0841	.0487	75	.00774	0.421	.0547	0.0570	.9596	.0404	.0421	.0277	.0169	
	2 PM		.1138	.0841	.0538	75	.00774	0.360	.0468	0.0538	.8698	.1302	.1496	.0986	.0145	
														.0632*	.0157*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-66	1 AM	35.7	.1118	.0815	.0567	76	.00761	0.304	.0825	0.0901	.9156	.0844	.0922	.0607	.0254	130
	2 AM		.1118	.0815	.0596	76		0.249	.0731	0.0874	.8364	.1636	.1956	.1289	.0226	
	1 PM		.1118	.0810	.0574	76		0.299	.0812	0.0901	.9017	.0983	.1090	.0718	.0251	
	2 PM		.1118	.0819	.0577	76		0.295	.0802	0.0866	.9260	.0740	.0799	.0527	.0247	
								0.292*		.0885*				.0785*	.0245*	
A-67	1 AM		.1118	.0819	.0540	76	.00761	0.341	.0926	0.1232	.7516	.2484	.3304	.2177	.0286	
	2 AM		.1118	.0819	.0555	76		0.322	.0875	0.1170	.7479	.2521	.3370	.2220	.0270	
	1 PM		.1118	.0819	.0525	75		.0359	.0975	0.1214	.8031	.1969	.2452	.1616	.0301	
	2 PM		.1118	.0819	.0528	75		0.355	.0965	0.1175	.8212	.1788	.2177	.1435	.0298	
								0.344*						.1550*	.0289*	
A-68	1 AM		.1118	.0819	.0486	74	.00761	0.407	.1106	0.1946	.5683	.4317	.7596	.5006	.0342	
	2 AM			.0819	.0456	74		0.443	.1203	0.1880	.6399	.3601	.5627	.3710	.0372	
	1 PM			.0823	.0426	75		0.482	.1310	0.1940	.6750	.3250	.4815	.3127	.0405	
	2 PM			.0823	.0455	75		0.447	.1214	0.1876	.6471	.3529	.5454	.3594	.0375	
								0.445*						.3859*	.0374*	
A-69	1 AM		.111	.081	.0356	76	.00755	0.560	.1509	.3029	.4982	.5018	1.0072	.6637	.0466	
	2 AM				.0380	76		0.531	.1431	.2809	.5094	.4906	0.9631	.6347	.0442	
	1 PM				.0345	75		0.574	.1547	.3032	.5102	.4898	0.9600	.6326	.0478	
	2 PM				.0378	75		0.533	.1437	.2869	.5009	.4991	0.9964	.6566	.0444	
					.0365			0.550*						.6469*	.0458*	
A-70	1 AM				.0416	73		0.486	.1310	.2022	.6479	.3521	0.5434	.3581	.0405	
	2 AM				.0449			0.446	.1202	.1911	.6290	.3710	0.5898	.3887	.0371	
	1 PM				.0410	75		0.494	.1332	.2019	.6597	.3403	0.5158	.3399	.0412	
	2 PM				.0437			0.460	.1240	.1931	.6422	.3578	0.5571	.3671	.0383	
					.0428			0.472						.3635*	.0393*	
A-71	1 AM				.0521	75		0.344	.0927	.1255	.7387	.2613	0.3537	.2331	.0286	
	2 AM				.0553			0.317	.0854	.1195	.7146	.2854	0.3994	.2632	.0264	
	1 PM				.0506			0.375	.1011	.1264	.7998	.2002	0.2503	.1649	.0312	
	2 PM				.0518			0.360	.0970	.1264	.7674	.2326	0.3831	.1997	.0300	
					.0527			0.349*						.2152	.0291	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-72	1 AM	35.7	0.111	0.081	.0581	76	.00755	0.283	.0763	.0937	.8231	.1769	.2149	.1416	.0346	130
	2 AM				.0606	76		0.252	.0679	.0900	.7544	.2456	.3256	.2146	.0210	
	1 PM				.0474	77		0.291	.0784	.0916	.8559	.1441	.1684	.1110	.0242	
	2 PM				.0582	77		0.281	.0757	.0876	.8642	.1358	.1571	.1035	.0234	
					.0586*			0.277*						.1427*	.0231*	
A-73	1 AM				.0280	73		0.654	.1763	.3246	.5431	.4569	.8413	.5544	.0545	
	2 AM				.0320	73		0.605	.1631	.3124	.5221	.4779	.9153	.6032	.0504	
	1 PM				.0284	73		0.649	.1749	.3391	.5158	.4842	.9387	.6186	.0540	
	2 PM				.0308	73		0.620	.1671	.2124	.5349	.4651	.8695	.5730	.0516	
					.0298*			0.632*						.5873*	.0526*	
A-74	1 AM	16.8			.0658	76		0.1877	.0238	.0494	.4818	.5182	1.0756	.7088	.0074	
	2 AM				.0679	76		0.1617	.0205	.0466	.4399	.5601	1.2732	.8390	.0063	
	1 PM				.0677	77		0.1642	.0208	.0531	.3917	.6083	1.5530	1.0234	.0064	
	2 PM				.0688	77		0.1506	.0191	.0508	.3760	.6240	1.6596	1.0937	.0059	
					.0676*			0.166*						.9162*	.0265*	
A-75	1 AM				.0263	76		0.6753	.0857	.1289	.6649	.3351	.5040	.3321	.0265	
	2 AM				.0261	76		0.6778	.0860	.1176	.7313	.2687	.3674	.2421	.0266	
	1 PM				.0271	78		0.6654	.0844	.1306	.6462	.3538	.5475	.3608	.0261	
	2 PM				.0254	78		0.6864	.0871	.1303	.6685	.3315	.4959	.3268	.0269	
					.0262*			0.676*						.3155*	.0265*	
A-76	1 AM				.0164	78		0.7975	.1012	.1986	.5096	.4904	.9623	.6342	.0313	
	2 AM				.0167	78		0.7938	.1007	.2019	.4988	.5013	1.0048	.6622	.0311	
	1 PM				.0162	77		0.8000	.1015	.1949	.5208	.4792	.9201	.6063	.0314	
	2 PM				.0163	77		0.7988	.1013	.1952	.5190	.4810	.9268	.6108	.0313	
					.0164*			0.4975*						.6284*	.0313*	
A-77	1 AM				.0276	74		0.6593	.0836	.1261	.6630	.3370	.5083	.3350	.0258	
	2 AM				.0269			0.6679	.0847	.1258	.6733	.3267	.4852	.3197	.0262	
	1 PM				.0264	75		0.6741	.0855	.1297	.6592	.3408	.5170	.3407	.0264	
	2 PM				.0237			0.7074	.0897	.1310	.6847	.3153	.4605	.3035	.0277	
								0.6772*						.3247*	.0265*	

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RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
		16.8	0.111	0.081			0.0075									60
A-78	1 AM				.0174	76		0.785	0.100	0.1878	0.532	0.468	0.880	0.580	0.0390	
	2 AM				.0178	76		0.780	0.099	0.1845	0.537	0.463	0.862	0.568	0.0306	
	1 PM				.0172	77		0.788	0.100	0.1842	0.543	0.457	0.842	0.555	0.0309	
	2 PM				.0177	77		0.781	0.099	0.1869	0.530	0.470	0.887	0.585	0.0306	
								0.784*		0.1859*				0.572*	0.0308*	
A-79	1 AM				.0584	78		0.279	0.035	0.0617	0.567	0.433	0.764	0.503	0.0108	
	2 AM				.0564	78		0.304	0.039	0.0628	0.621	0.379	0.610	0.402	0.0121	
	1 PM				.0572	75		0.294	0.037	0.0635	0.583	0.417	0.808	0.532	0.0114	
	2 PM				.0583	75		0.280	0.036	0.0643	0.560	0.440	0.786	0.518	0.0111	
								0.289*		0.0631*				0.489*	0.0114*	
A-80	1 AM				.0237	77		0.707	0.090	0.1171	0.769	0.231	0.300	0.198	0.0278	
	2 AM				.0235	77		0.707	0.090	0.1193	0.754	0.246	0.326	0.215	0.0278	
	1 PM				.0230	76		0.716	0.091	0.1151	0.791	0.209	0.264	0.174	0.0281	
	2 PM				.0234	76		0.711	0.090	0.1146	0.785	0.215	0.274	0.181	0.0281	
								0.710*		0.1165*				0.192*	0.0280*	
A-81	1 AM				.0161	76		0.801	0.102	0.1773	0.575	0.425	0.739	0.487	0.0315	
	2 AM				.0165	76		0.796	0.101	0.1740	0.580	0.420	0.724	0.477	0.0312	
	1 PM				.0153	76		0.811	0.103	0.1834	0.562	0.438	0.779	0.513	0.0318	
	2 PM				.0168	76		0.793	0.101	0.1691	0.597	0.403	0.675	0.445	0.0312	
								0.800*		0.1760*				0.481*	0.0314*	
A-82	1 AM				.0164	76		0.798	0.101	0.1225	0.824	0.176	0.214	0.141	0.0312	
	2 AM				.0180	76		0.778	0.099	0.1198	0.826	0.174	0.211	0.139	0.0306	
	1 PM				.0159	77		0.804	0.102	0.1308	0.780	0.220	0.282	0.186	0.0315	
	2 PM				.0175	77		0.784	0.099	0.1256	0.788	0.212	0.269	0.177	0.0306	
								0.791*		0.1247*				0.161*	0.0310*	
A-83	1 AM				.0085	76		0.895	0.114	0.2010	0.567	0.433	0.764	0.503	0.0352	
	2 AM				.0096	76		0.881	0.112	0.1779	0.630	0.370	0.587	0.387	0.0346	
	1 PM				.0064	76		0.921	0.117	0.1972	0.593	0.407	0.686	0.452	0.0362	
	2 PM				.0084	76		0.896	0.114	0.1773	0.643	0.357	0.555	0.366	0.0352	
								0.898*		0.1884*				0.427*	0.0353*	

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RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-84	1 AM	16.8	0.111	0.081	0.0050	75	.0075	0.938	0.119	0.3288	0.362	0.638	1.762	1.161	0.0368	60
	2 AM				0.0079	75		0.902	0.114	0.2814	0.405	0.595	1.469	0.968	0.03	
	1 PM				0.0012	77		0.985	0.125	0.3111	0.402	0.598	1.487	0.980	0.0386	
	2 PM				0.0027	77		0.954	0.121	0.3100	0.390	0.610	1.564	1.031	0.0374	
								0.945*		0.3078*				1.035*	0.0370*	
A-86	1 AM				0.0237	75		0.707	0.090	0.1030	0.874	0.126	0.144	0.095	0.0278	
	2 AM				0.0264	75		0.674	0.085	0.0984	0.864	0.136	0.157	0.103	0.0263	
	1 PM				0.0234	76		0.711	0.090	0.1065	0.845	0.155	0.183	0.121	0.0278	
	2 PM				0.0261	76		0.678	0.086	0.1037	0.829	0.171	0.206	0.136	0.0266	
								0.693*		0.1029*				0.114*	0.0271*	
A-87	1 AM	35.7			0.0307	76		0.621	0.167	0.2203	0.758	0.242	0.319	0.210	0.0516	130
	2 AM				0.0336	76		0.585	0.158	0.2148	0.736	0.264	0.359	0.237	0.0488	
	1 PM				0.0320	76		0.605	0.163	0.2230	0.731	0.269	0.368	0.243	0.0504	
	2 PM				0.0337	76		0.584	0.157	0.2175	0.722	0.278	0.385	0.254	0.0485	
								0.599*		0.2189*				0.236*	0.0498*	
A-88	1 AM				0.0438	77		0.459	0.124	0.1416	0.876	0.124	0.142	0.094	0.0383	
	2 AM				0.0454	77		0.441	0.119	0.1402	0.849	0.151	0.178	0.117	0.0368	
	1 PM				0.0437	77		0.460	0.124	0.1486	0.834	0.166	0.199	0.131	0.0383	
	2 PM				0.0456	77		0.437	0.118	0.1429	0.826	0.174	0.211	0.139	0.0365	
								0.449*		0.1433*				0.120*	0.0375*	
A-89	1 AM				0.0521	76		0.357	0.096	0.1083	0.886	0.114	0.129	0.085	0.0297	
	2 AM				0.0526	76		0.351	0.095	0.1074	0.885	0.115	0.130	0.086	0.0294	
	1 PM				0.0548	79		0.323	0.087	0.1132	0.769	0.231	0.300	0.198	0.0269	
	2 PM				0.0585	79		0.278	0.075	0.1104	0.679	0.321	0.473	0.312	0.0232	
								0.327*		0.1098*				0.170*	0.0273*	
A-90	1 AM				0.0218	76		0.731	0.197	0.3415	0.577	0.423	0.733	0.483	0.0609	
	2 AM				0.0219	76		0.730	0.197	0.3371	0.584	0.416	0.712	0.469	0.0609	
	1 PM				0.0225	76		0.722	0.195	0.3481	0.560	0.440	0.786	0.518	0.0603	
	2 PM				0.0239	76		0.705	0.190	0.3315	0.573	0.427	0.745	0.491	0.0587	
								0.722*		0.3396*				0.490*	0.0602*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-91	1 AM	49.5	0.111	0.081	0.0323	75	.00755	0.601	0.225	0.2553	0.633	0.367	0.580	0.382	0.0695	180
	2 AM				0.0363	75		0.552	0.206	0.3476	0.593	0.407	0.686	0.452	0.0637	
	1 PM				0.0312	76		0.615	0.230	0.3558	0.646	0.354	0.548	0.361	0.0711	
	2 PM				0.0347	76		0.572	0.214	0.3459	0.619	0.381	0.616	0.406	0.0661	
								0.585*		0.3512*				0.400*	.067.	
A-92	1 AM				0.0396	76		0.511	0.191	0.2341	0.816	0.184	0.225	0.148	0.0590	
	2 AM				0.0422	76		0.479	0.179	0.2313	0.774	0.226	0.292	0.192	0.0553	
	1 PM				0.0410	76		0.494	0.185	0.2330	0.294	0.206	0.259	0.171	0.0572	
	2 PM				0.0435	76		0.463	0.173	0.2269	0.762	0.238	0.312	0.206	0.0535	
								0.487*		0.2312*				0.179*	0.0563*	
A-93	1 AM				0.0507	77		0.374	0.140	0.1443	0.970	0.030	0.031	0.020	0.0433	
	2 AM				0.0519	77		0.359	0.134	0.1429	0.938	0.062	0.066	0.043	0.0414	
	1 PM				0.0553	77		0.317	0.118	0.1462	0.807	0.193	0.239	0.158	0.0365	
	2 PM				0.0542	77		0.331	0.124	0.1457	0.851	0.149	0.175	0.115	0.0383	
								0.345*		0.1448*				0.084*	0.0399*	
A-94	1 AM				0.0583	76		0.280	0.105	0.1074	0.978	0.022	0.022	0.014	0.0324	
	2 AM				0.0591	76		0.270	0.101	0.1050	0.962	0.038	0.040	0.026	0.0312	
	1 PM				0.0602	76		0.257	0.096	0.1052	0.913	0.087	0.095	0.063	0.0297	
	2 PM				0.0599	76		0.260	0.097	0.1043	0.930	0.070	0.075	0.449	0.0300	
								0.267*		0.1055*				0.038*	0.0308*	
A-95	1 AM				0.0279	76		0.656	0.1768	0.3613	0.4893	0.5107	1.0437	0.6878	0.0546	130
	2 AM				0.0321	76		0.604	0.1628	0.3569	0.4562	0.5438	1.1920	0.7855	0.0503	
	1 PM				0.0385	76		0.648	0.1747	0.3635	0.4806	0.5194	1.0807	0.7122	0.0540	
	2 PM				0.0310	76		0.617	0.1663	0.3580	0.4645	0.5355	1.1529	0.7598	0.0514	
					0.0399			0.631*		0.3599*				0.7363*	0.0526*	
A-96	1 AM				0.0382	76		0.527	0.1420	0.2341	0.6066	0.3934	0.6485	0.4274	0.0439*	
	2 AM				0.0492	76		0.504	0.1258	0.2341	0.5801	0.4199	0.7238	0.4770	0.0420	
	1 PM				0.0400	77		0.506	0.1364	0.2331	0.5852	0.4148	0.7088	0.4671	0.0421	
	2 PM				0.0422	77		0.479	0.1291	0.2325	0.5553	0.4447	0.8008	0.5277	0.0399	
					0.0402			0.504*		0.2335*				0.4748*	0.0420*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-97	1 AM	35.7	0.111	0.081	0.0485	77	.00755	0.401	0.1081	0.1383	0.7816	0.2184	0.2794	0.1841	0.0334	130
	2 AM				0.0493	77		0.391	0.1054	0.1377	0.7654	0.2346	0.3065	0.2020	0.0326	
	1 PM				0.0529	77		0.347	0.0935	0.1424	0.6566	0.3434	0.5230	0.3447	0.0289	
	2 PM				0.0496	77		0.388	0.1046	0.1424	0.7346	0.2654	0.3613	0.2381	0.0223	
					0.0501*			0.382*		0.1402*				0.2422*	0.0318*	
A-98	1 AM				0.0544	75		0.328	0.0884	0.1030	0.8583	0.1417	0.1651	0.1088	0.0273	
	2 AM				0.0424	75		0.353	0.0951	0.1035	0.9188	0.0812	0.0884	0.0583	0.0294	
	1 PM				0.0517	75		0.362	0.0976	0.1041	0.9376	0.0624	0.0666	0.0439	0.0302	
	2 PM				0.0538	75		0.336	0.0906	0.1045	0.8670	0.1330	0.1534	0.1011	0.0280	
					0.0531			0.345*		0.1038*				0.0780*	0.0287*	
A-99	1 PM				0.0558	73		0.311	0.0839	0.1025	0.8185	0.1815	0.2217	0.1461	0.0259	
	2 PM				0.0564	73		0.304	0.0819	0.1049	0.7807	0.2193	0.2809	0.1851	0.0253	
					0.0561			0.308*		0.1037*				0.1656*	0.0256*	
A-100	1 AM				0.0555	73		0.315	0.0849	0.0993	0.8550	0.1450	0.1696	0.1118	0.0262	
	2 AM				0.0556	73		0.314	0.0846	0.1006	0.8410	0.1590	0.1891	0.1246	0.0261	
	1 PM				0.0537	73		0.337	0.0908	0.1006	0.9026	0.0974	0.1079	0.0711	0.0281	
	2 PM				0.0522	73		0.356	0.0960	0.1015	0.9458	0.0542	0.0573	0.0378	0.0297	
					0.0543			0.331*		0.1005*				0.0863*	0.0275*	
A-101	1 AM				0.0482	73		0.405	0.1092	0.1426	0.7658	0.2342	0.3058	0.2015	0.0337	
	2 AM				0.0499	73		0.384	0.1035	0.1412	0.7330	0.2670	0.3643	0.2401	0.0320	
	1 PM				0.0473	73		0.416	0.1121	0.1418	0.7906	0.2094	0.2649	0.1746	0.0346	
	2 PM				0.0498	73		0.385	0.1038	0.1412	0.7351	0.2649	0.3604	0.2375	0.0321	
					0.0488			0.398*		0.1417*				0.2134*	0.0331*	
A-102	1 AM				0.0352	74		0.565	0.1523	0.2255	0.6754	0.3246	0.4806	0.3167	0.0471	
	2 AM				0.0381	74		0.530	0.1429	0.2211	0.6463	0.3537	0.5473	0.3607	0.0442	
	1 PM				0.0341	73		0.579	0.1561	0.2243	0.6959	0.3041	0.4370	0.2880	0.0482	
	2 PM				0.0360	73		0.556	0.1499	0.2204	0.6801	0.3199	0.4704	0.3100	0.0463	
					0.0359			0.558*		0.2228*				0.3189*	0.0465*	
A-103	1 AM				0.0226	72		0.721	0.1943	0.3485	0.5575	0.4425	0.7937	0.5230	0.0600	
	2 AM				0.0268	72		0.669	0.1803	0.3496	0.5157	0.4843	0.9391	0.6189	0.0557	
	1 PM				0.0237	70		0.707	0.1906	0.3498	0.5449	0.4551	0.8352	0.5504	0.0589	
	2 PM				0.0272	70		0.664	0.1790	0.3464	0.5167	0.4833	0.9354	0.6164	0.0553	
					0.0251			0.690*		0.3486*				0.5772*	0.0575*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
		35.7	0.111	0.081			0.00755									130
A-104	1 AM				0.0234	69		0.711	0.1916	0.3549	0.5399	0.4601	0.8522	0.5616	0.0592	
	2 AM				0.0250	69		0.691	0.1862	0.3471	0.5364	0.4636	0.8643	0.5696	0.0575	
	1 PM				0.0226	69		0.721	0.1943	0.3549	0.5475	0.4525	0.8265	0.5447	0.0600	
	2 PM				0.0279	69		0.565	0.1768	0.3471	0.5094	0.4906	0.9631	0.6547	0.0546	
					0.0247*			0.695*		0.3510*				0.5776*	0.0578*	
A-105	1 AM				0.0351	71		0.567	0.1528	0.2352	0.6497	0.3503	0.5392	0.3553	0.0472	
	2 AM				0.0383	71		0.527	0.1420	0.2324	0.6110	0.3890	0.6367	0.4196	0.0439	
	1 PM				0.0326	70		0.598	0.1612	0.2300	0.7009	0.2991	0.4267	0.2812	0.0498	
	2 PM				0.0353	70		0.564	0.1520	0.2356	0.6452	0.3548	0.5499	0.3624	0.0470	
					0.0353*			0.564*		0.2332*				0.3546*	0.0471*	
A-106	1 AM				0.0483	71		0.404	0.1089	0.1565	0.6958	0.3042	0.4372	0.2881	0.0339	
	2 AM				0.0456	71		0.437	0.1178	0.1529	0.7704	0.2296	0.2980	0.1964	0.0364	
	1 PM				0.0469	71		0.421	0.1135	0.1520	0.7467	0.2533	0.3392	0.2235	0.0351	
	2 PM				0.0471	71		0.419	0.1129	0.1473	0.7665	0.2335	0.3046	0.2007	0.0349	
					0.0470*			0.420*		0.1522*				0.2272*	0.0351*	
A-107	1 AM				0.0527	71		0.349	0.0941	0.1064	0.8844	0.1159	0.1310	0.0863	0.0291	
	2 AM				0.0523	71		0.354	0.0954	0.1066	0.8949	0.1051	0.1174	0.0774	0.0295	
	1 PM				0.0483	71		0.404	0.1089	0.1138	0.9569	0.0431	0.0450	0.0297	0.0337	
	2 PM				0.0524	71		0.353	0.0951	0.1103	0.8622	0.1378	0.1598	0.1053	0.0294	
					0.0514*			0.365*		0.1093*				0.0747*	0.0304*	
A-108	1 AM				0.0235	73		0.710	0.1914	0.3966	0.4826	0.5174	1.0721	0.7065	0.0591	
	2 AM				0.0261	73		0.678	0.1827	0.3766	0.4851	0.5149	1.0614	0.6995	0.0565	
	1 PM				0.0207	73		0.744	0.2005	0.3600	0.5569	0.4431	0.7957	0.5244	0.0620	
	2 PM				0.0251	73		0.690	0.1860	0.3689	0.5042	0.4958	0.9833	0.6480	0.0575	
					0.0239*			0.706*		0.3755*				0.6446*	0.0588*	60
A-109	1 AM				0.0288	71		0.644	0.0778	0.1132	0.6873	0.3127	0.4550	0.2998	0.0240	
	2 AM				0.0270	71		0.667	0.0806	0.1140	0.7070	0.2930	0.4144	0.2731	0.0249	
	1 PM				0.0250	71		0.691	0.0835	0.1103	0.7570	0.2430	0.3210	0.2115	0.0258	
	2 PM				0.0260	71		0.679	0.0820	0.1110	0.7387	0.2613	0.3537	0.2331	0.0253	
					0.0267*			0.670*		0.1121*				0.2544*	0.0250*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-110	1 AM	16.8	0.111	0.081	0.0179	72	.00755	0.779	.0988	.1437	.6875	.3125	.4545	.2995	.0305	60
	2 AM				0.0208	72		0.743	.0942	.1418	.6643	.3357	.5053	.3330	.0291	
	1 PM				0.0182	72		0.774	.0982	.1407	.6979	.3021	.4329	.2853	.0303	
	2 PM				0.0206	72		0.746	.0946	.1457	.6493	.3507	.5401	.2559	.0292	
								0.761*		.1430*				.3184*	.0298*	
A-111	1 AM				0.0597	72		0.263	.0709	.1285	.5518	.4482	.8123	.5353	.0219	130
	2 AM				0.0539	72		0.335	.0903	.1276	.7077	.2923	.4130	.2722	.0279	
	1 PM				0.0531	72		0.344	.0927	.1247	.7434	.2566	.3452	.2275	.0286	
	2 PM				0.0542	72		0.331	.0892	.1295	.6888	.3112	.4518	.2977	.0276	
								0.318*		.1276*				.3332*	.0265*	
A-112	1 AM				0.0481	72		0.406	.1094	.1637	.6683	.3317	.4963	.3271	.0338	
	2 AM				0.0469	72		0.421	.1135	.1581	.7179	.2821	.3930	.2590	.0351	
	1 PM				0.0489	72		0.396	.1067	.1587	.6723	.3277	.4874	.3212	.0330	
	2 PM				0.0475	72		0.414	.1116	.1665	.6703	.3297	.4919	.3242	.0345	
								0.409*		.1618*				.3079*	.0341*	
A-113	1 PM	35.7			0.0355	72		0.562	.1515	.2436	.6219	.3781	.6080	.4007	.0468	
	2 PM				0.0353	72		0.564	.1520	.2414	.6297	.3703	.5881	.3875	.0470	
										.2425*				.3941*	.0469*	
A-114	1 AM				0.0374	71		0.539	.1453	.3925	.3702	.6298	1.7012	1.1211	.0449	
	2 AM				0.0387	71		0.522	.1407	.3947	.3565	.6435	1.8050	1.1895	.0435	
	1 PM				0.0250	71		0.691	.1862	.3513	.5300	.4700	.8868	.5844	.0575	
	2 PM				0.0283	71		0.651	.1755	.3614	.4856	.5144	1.0593	.6981	.0542	
										.3750*				.8983*	.0500*	
A-115	1 AM		.0695	0.051	0.0262	70	.00472	.4863	.0819	.2089	.3921	.6079	1.5504	1.0217	.0253	
	2 AM				0.0291	70		.4294	.0724	.2066	.3504	.6496	1.8539	1.2217	.0224	
										.2078*				1.1217*	.0239*	
A-116	1 PM		0.144	0.105	0.0474	70	.00979	.5486	.1917	.2774	.6911	.3089	.4470	.2946	.0592	
	2 PM				0.0495	70		.5286	.1847	.2768	.6673	.3327	.4986	.3286	.0571	
										.2771*				.3116*	.0582*	

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RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-117	1 PM	35.7	0.199	0.145	0.0725	73	.01353	0.500	.2415	.3418	.7066	.2934	.4152	.2736	.0746	130
	2 PM				0.0702	73	.01353	0.5159	.2492	.3479	.7163	.2837	.3961	.2610	.0770	
										.3449*				.2673*	.0758*	
A-118	1 PM		0.144	0.105	0.0599	72	.00979	.4295	.1501	.1778	.8442	.1558	.1846	.1157	.0464	
	2 PM		0.114	0.105			.00979	.4314	.1508	.1792	.8415	.1585	.1884	.1242	.0466	
										.1785*				.1197*	.0465*	
A-119	1 AM		0.071	0.052	0.0279	74	.00482	.4635	.0798	.1230	.6488	.3512	.5413	.3567	.0247	
	2 AM		0.071	0.052	0.0307	74	.00482	.4096	.0705	.1211	.5822	.4178	.7176	.4729	.0218	
										.1221*				.4148*	.0233*	
A-121	1 PM		0.111	0.081	0.0396	72	.00755	.5111	.1378	.2231	.6176	.3824	.6192	.4081	.0426	
	2 PM				0.0387	72		.5222	.1407	.2247	.6262	.3738	.5969	.3934	.0435	
										.2239*				.4008*	.0431*	
A-122	1 A				0.0512	74		.3679	.0992	.2372	.4182	.5818	1.3912	.9168	.0307	
	1 B				0.0506	74		.3753	.1012	.2372	.4266	.5734	1.3441	.8858	.0313	
	2 A				0.0515	74		.3642	.0982	.2316	.4240	.5760	1.3585	.8953	.0303	
	2 B				0.0477	74		.4111	.1108	.2316	.4784	.5216	1.0903	.7185	.0342	
										.2344*				.8541*	.0316*	
A-123	1 A				0.0387	74		.5222	.1407	.2244	.6270	.3730	.5949	.3920	.0435	
	1 B				0.0385	74		.5247	.1414	.2278	.6207	.3793	.6111	.4027	.0437	
	2 A				0.0390	74		.5185	.1398	.2272	.6153	.3847	.6252	.4120	.0432	
	2 B				0.0396	74		.5111	.1378	.2294	.6007	.3993	.6647	.4380	.0426	
										.2272*				.4112*	.0433*	
A-124	1 A				0.0323	76		.6012	.1620	.3580	.4525	.5475	1.2099	.7973	.0501	
	1 B				0.0323	76		.6012	.1620	.3646	.4443	.5557	1.2507	.8242	.0501	
	2 A				0.0334	76		.5877	.1584	.3745	.4230	.5770	1.3641	.8989	.0489	
	2 B				0.0335	76		.5864	.1581	.3646	.4336	.5664	1.3063	.8609	.0489	
										.3654*				.8453*	.0495*	

RESULTS OF HEATLESS DESORPTION CARBON DIOXIDE EXPERIMENTS

Run	Cycle	F	P_f	P_f'	P_e'	T	V_f	V_r	V_c	V	V_d	V_{ad}	α	B	C	S_v
A-125	1	35.7	0.111	0.081	.0277	73	.00755	.6580	.1774	.3522	.5037	.4963	.9853	.6493	.0548	130
	1				.0276	73		.6593	.1777	.3534	.5028	.4972	.9889	.6517	.0549	
	2				.0292	73		.6395	.1724	.3489	.4941	.5059	1.0239	.6748	.0533	
	2				.0285	73		.6481	.1747	.3511	.4976	.5024	1.0096	.6653	.0540	
									.1756*					.6603*	.0543*	
A-126	1				.0511	72		.3691	.0995	.1418	.7017	.2983	.4251	.2801	.0307	
	2				.0499	72		.3840	.1035	.1457	.7104	.2896	.4077	.2687	.0320	
									.1015*					.2744*	.0314*	
A-127	1				.0489	73		.3963	.1068	.1376	.7762	.2238	.2883	.1920	.0330	
	2				.0483	73		.4037	.1088	.1429	.7614	.2386	.3134	.2065	.0336	
									.1078*					.1983*	.0333*	
A-128	1				.0485	76		.4012	.1081	.1388	.7788	.2212	.2840	.1872	.0334	
	2				.0469	76		.4210	.1135	.1454	.7806	.2194	.2811	.1852	.0351	
									.1108*					.1862*	.0343*	
A-129	1			0.096	.0227	74		.7635	.2058	.4091	.5031	.4969	.9877	.6509	.0636	
	2				.0245	74		.7448	.2007	.4146	.4841	.5159	1.0657	.7023	.0620	
									.2033					.6766	.0628	
A-130	1				.0469	72		.5115	.1379	.2897	.4760	.5240	1.1008	.7254	.0426	
	2				.0442	72		.5396	.1454	.2924	.4973	.5027	1.0109	.6662	.0449	
									.1417*					.6958*	.0438*	
A-131	1				.0553	74		.4240	.1143	.1810	.6315	.3685	.5835	.3845	.0353	
	2				.0528	74		.4500	.1213	.1827	.6639	.3361	.5063	.3337	.0375	
									.1178*					.3591*	.0364*	
A-132	1				.0572	74		.4042	.1089	.1358	.8019	.1981	.2470	.1628	.0337	
	2				.0598			.3771	.1016	.1347	.7543	.2457	.3257	.2146	.0314	
									.1053*					.1887*	.0326*	

Appendix 7.7

Performance of Heatless Desorption Drying Runs

Run No.	Date Run Started	Spece Velocity CFH/lb. of bed	P/F	Cycle No.	Effluent H_2O Concentration PPM
		Runs D-1 thru D-7 were preliminary runs to checkout system performance			
D-8	10-2-69	156	1.21	720	14
D-9	10-3-69	156	1.08	720	15
				1440	395
				2160	650
				4320	412
D-10	10-7-69	System developed leak			
D-11	10-9-69	159	1.15	720	645
				1440	422
				3600	361
D-12	10-15-69	90		720	245
				1440	350
				2160	305
				4320	390
D-13	10-20-69	90		720	352
				1440	166
				2160	155
				2880	136
				3600	66
				5760	95
				6580	60
D-14	10-31-69	48	1.03	720	21
				1440	9
				4600	55
				5320	770
				6040	512
				6760	512
D-15	11-6-69	48	1.12	720	355
				1440	165
				4600	41
				5520	16
				6040	16
D-16	11-13-69	48	1.14	720	11
				1440	8
				2160	4
				4600	4
D-17	11-18-69	28	1.10	720	3
				1440	4
				2160	4
				5240	4

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Appendix 7.7

Performance of Heatless Desorption Drying Runs

Run No.	Date of Run Started	Space Velocity CFH/lb of bed	P/F	Cycle No.	Effluent H_2O Concentration PPM
D-18	11-25-69	28	1.05	720	4
				1440	5
				5040	8
				5760	8
D-19	System Leak – Run aborted				
D-20	12-23-69	28	1.05	720	11
				5000	140
				7150	140
				9300	250
				10,020	250
				11,000	250

Runs D-21 and D-22 Aborted because of equipment problems

Run No.	Date of Run Started	Space Velocity CFH/lb of bed	P/F	Cycle No.	Effluent H_2O Concentration PPM
D-23	1-16-70	48	1.03	720	330
				2880	520
				3600	375
				4320	416
				5040	416

Two Zone Bed Runs

All two Zone Bed Runs use 50 gms SiO_2 plus a specified charge of molecular sieves

Run No.	Date of Run Started	Space Velocity CFH/lb of bed	P/F	Cycle No.	Effluent H_2O Concentration PPM
D-24	1-26-70	48*	1.03	720	24
Molecular Sieves Added – 25.0 gms 5A				2880	24
				3600	20
				4320	20
				10,020	20
D-25	1-30-70	48*	1.03	1440	3
Molecular Sieves Added – 12.5 gms 5A				2160	17
				2900	17
				6500	44
				7220	147
				10,120	625
				16,560	416
				17,280	416
D-26	2-24-70	Run Aborted because of Hygrometer breakdown			
D-27	2-26-70	48*	1.03	720	8
Molecular Sieves Added – 12.5 gms 13.X				2972	1
				2412	13
				5312	110
				6752	520
				10,352	250
				11,070	250
				11,790	250

* Space velocity based on silica gel charge only

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Appendix 7.7

Performance of Heatless Desorption Drying Runs

Run No.	Date of Run Started	CFH/lb. of bed	P/F	Cycle No.	Effluent H$_2$O Concentration PPM
D-28	Run aborted because of pump failure				
D-29	4-21-70	48*	1.03	720	1
Molecular Sieve Added - 25 gms 13X				5000	7
				7900	5
				12,200	40
				15,100	33
				15,820	20
				17,900	15
	Run aborted because of pump failure				
D-30	5-20-70	48*	1.03	1440	44
				3600	9
	Molecular Sieve Added - 18 gms 13X			4320	11
				7200	13
				7920	92
				8640	147
				9360	257
				11,520	370
				12,240	250
				12,960	220
				13,680	220
				15,840	220

* Space Velocity based on silica gel charge only